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LSSA

LOW-COST SILICON SOLAR ARRAY

PROJECT

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Project QUARTERLY REPORT-5

FOR THE PERIOD APRIL 1977- JUNE 1977

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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This report describes work performed in the field of photovoltaic research by the Low-Cost Silicon Solar Array Project of Jet Propulsion Laboratory. LSSA Project activities conducted during the period April-June 1977, are detailed, and background technical information is furnished.

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CONTENTS

I. INTRODUCTION AND PROJECT OVERVIEW ---------------------------- 1-1

A. INTRODUCTION -- 1-1

B. PROJECT OVERVIEW -- 1-1

II. PROJECT ANALYSIS AND INTEGRATION AREA ----------------------- 2-1

A. PLANNING AND INTEGRATION ---------------------------------- 2-1

B. ARRAY TECHNOLOGY COST ANALYSIS ---------------------------- 2-1

1. Uniform Costing Methodology ------------------------------- 2-1

2. Industry Simulation --------------------------------------- 2-1

3. Price Goal Allocation ------------------------------------- 2-1

C. ARRAY LIFE CYCLE ANALYSIS --------------------------------- 2-3

D. ECONOMICS AND INDUSTRIALIZATION --------------------------- 2-3

III. TECHNOLOGY DEVELOPMENT AREA -------------------------------- 3-1

A. SILICON MATERIAL TASK ------------------------------------- 3-1

1. Technical Goals --- 3-1

2. Organization and Coordination of the Silicon Material Task Effort ---------------------------------- 3-1

3. Silicon Material Task Contracts --------------------------- 3-3

4. Silicon Material Task Technical Background ---------------- 3-3

5. Summary of Progress --------------------------------------- 3-7

B. LARGE-AREA SILICON SHEET TASK ----------------------------- 3-9

1. Technical Goals --- 3-10

2. Organization and Coordination of the Large-Area Silicon Sheet Task Effort ------------------------------ 3-10

3. Large-Area Silicon Sheet Task Contracts ------------------- 3-10

4. Large-Area Silicon Sheet Task Technical Background ---- 3-12

5. Summary of Progress --------------------------------------- 3-19

C. ENCAPSULATION TASK ---------------------------------- 3-20

1. Technical Goals ---------------------------------- 3-21

2. Organization and Coordination of the Encapsulation Task Effort ---------------------------------- 3-21

3. Encapsulation Task Contracts ---------------------------------- 3-22

4. Encapsulation Task Technical Background ---------------------------------- 3-22

5. Summary of Progress ---------------------------------- 3-28

IV. PRODUCTION PROCESS AND EQUIPMENT AREA ---------------------------------- 4-1

A. TECHNICAL GOALS ---------------------------------- 4-1

B. ORGANIZATION AND COORDINATION OF THE PRODUCTION PROCESS AND EQUIPMENT AREA EFFORT ---------------------------------- 4-1

C. SUMMARY OF PROGRESS ---------------------------------- 4-3

1. Process Activities ---------------------------------- 4-3

2. Assessment of Advanced Panel Design ---------------------------------- 4-8

V. ENGINEERING AREA ---------------------------------- 5-1

VI. OPERATIONS AREA ---------------------------------- 6-1

A. SUMMARY OF PROGRESS ---------------------------------- 6-1

B. EXPANDED NARRATIVE OF ACTIVITIES ---------------------------------- 6-1

1. Large-Scale Production (LSP) Task ---------------------------------- 6-1

2. Environmental Testing ---------------------------------- 6-3

3. Field Testing ---------------------------------- 6-6

4. Performance Measurements and Standards ---------------------------------- 6-7

5. Failure Analysis ---------------------------------- 6-8

B. THERMAL TEST RESULTS ---------------------------------- 6-5

VII. REFERENCES ---------------------------------- 7-1

Figures

3-1. Capillary Die Growth (EFG and CAST) - Mobile-Tyco and IBM ---- 3-13

3-2. Inverted Stepanov Technique - RCA ---- 3-14

3-3. Web-Dendritic Growth - University of South Carolina ---- 3-15

3-4. Laser Zone Crystallization - Motorola ---- 3-16

3-5. Chemical Vapor Deposition on Low-Cost Substrates - Rockwell International ---- 3-17

3-6. Crystal Growth Using the Heat Exchanger Method - Crystal Systems ---- 3-18

4-1. Production Process and Equipment Area Schedule ---- 4-2

4-2. Total Reflection for Polished and Textured Surfaces ---- 4-5

4-3. Cost Summary of Solar Cell Manufacturing Sequence Utilizing Screen Printing ---- 4-6

4-4. Costs of Production at 50 MW/yr and 500 MW/yr ---- 4-7

4-5. Xerox-EOS Mechanical Contact Design ---- 4-9

5-1. Correlation of Hail-Induced Damage with Drainage Due to Dropped Steel Balls and Static-Loaded Steel Balls ---- 5-3

5-2. Cell Shunt Resistance for Block II Modules ---- 5-5

6-1. Typical I-V Curve Produced by Pasadena Field Test Site Automated Data Acquisition System ---- 6-7

6-2. Separation of Metallization from Back of Cell ---- 6-11

6-3. Carbonized Material Where the Interconnect to the Bottom of the Cell Was Connected ---- 6-11

Tables

2-1. Current Price Goals ---- 2-2

2-2. Conversion Formula ---- 2-4

3-1. Organization of the Silicon Material Task Effort ---- 3-2

3-2. Silicon Material Task Contractors ---------------------- 3-4

3-3. Large-Area Silicon Sheet Task Contractors ------------- 3-11

3-4. Encapsulation Task Contractors ------------------------ 3-23

4-1. Production Process and Equipment Area Contractors ----- 4-4

5-1. Observed Hail Damage to Block II Modules -------------- 5-2

6-1. Large-Scale Production Task Module Testing ------------ 6-4

6-2. Module Testing A3 Task Experimental Modules ----------- 6-6

6-3. Summary of P/FR Activity ------------------------------ 6-9

6-4. Breakdown of P/FR's By Problem Cause ------------------ 6-10

SECTION I

INTRODUCTION AND PROJECT OVERVIEW

A. INTRODUCTION

This report describes the activities of the Low-Cost Silicon Solar Array Project during the period April through June, 1977. The LSSA Project is assigned responsibility for advancing silicon solar array technology while encouraging industry to reduce the price of arrays to a level at which photovoltaic electric power systems will be competitive with more conventional power sources early in the next decade. Set forth here are the goals and plans with which the Project intends to accomplish this, and the progress that was made during the quarter.

The Project objective is to develop the national capability to produce low-cost, long-life photovoltaic arrays at a rate greater than 500 megawatts per year and a price of less than $500* per kilowatt peak by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 years.

B. PROJECT OVERVIEW

Additional focus was brought to economic analysis as an area of intensified activity during this quarter. The convergence of these efforts occurred at the 6th Project Integration Meeting, which was held May 4-5 at Caltech. Task and area managers presented the results of their analyses, undertaken primarily from a cost standpoint, of the feasibility of meeting 1982 goals. This presentation formed the keystone of vigorous discussions on whether the 1982 goals are technically feasible, economically feasible, and feasible within the context of the present and anticipated industry situation. The consensus was that the goal of $2/W by 1982 was technically feasible, and that it appeared economically feasible given substantial and effective government support. Some industry representatives, however, sharply questioned the risk implied by the plans. They noted that severe problems of large capital investment versus rapid obsolescence of facilities and equipment could arise as the technology advances quickly toward the 1986 goals.

Economic analysis of production processes intensified during this quarter. Detailed cost summaries developed by contractors were refined and were reviewed by Project personnel, particularly in regard to 1982 goals. Studies of the effects of process variables on costs were continued. The most cost-effective process sequence forecast a cost of $.273/W in processing wafers into finished modules, given a production rate of 50 MW/yr.

*In 1975 dollars.

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Efforts to reduce the cost of semiconductor-grade silicon advanced toward experimental plant construction as major mini-plant elements of two of the more mature processes were successfully tested. Production of Si from SiH_4 proceeded rapidly at high volume; however, these early experiments suffered from considerable contamination, due to interactions with construction materials. Design analysis of the 25 MT/yr process-system development facility, which will refine Si from the Zn reduction of $SiCl_4$ in a fluidized bed reactor, progressed by the refinement of the calculations for the process flow diagram and material/energy balances.

In the area of ribbon growth and slicing, several techniques advanced well, and one failed to prove its feasibility. Ribbons of 11%-12% efficiency were grown using the EFG process, and the RTR method demonstrated ribbons 2.5 cm wide grown at 2.5 cm/min. Recrystallization was found to be very sluggish in the hot-rolling process, and the task of enlarging the grain size to meet requirements was found to be not cost-effective. Both the multiblade and the multiwire slicing techniques explored during this quarter were able to yield 22 wafers/cm of silicon ingot length.

A universal test specimen program was developed to test nine different encapsulation systems with both natural and accelerated weathering. The fabrication of test mini-modules using various candidate encapsulant systems was completed, except for those using difficultly-processed thermoplastic materials. Outdoor testing at Desert Sunshine Environmental Testing was begun with candidate materials previously identified as promising in indoor testing.

Testing completed during this quarter showed that opaque, closed-back modules mounted in a simulated residential roof mounting generate about 5% less power than open-back modules, due to thermal losses. Completion of the first phase of the hail impact study showed that the threat to modules from hail in the U.S. Midwest region could be quite severe.

Three months of production experience with the Block II (130 kW) procurement indicated that manufacturers were having great difficulty in meeting their delivery schedules; additionally, about 20% of the modules were rejected during source inspection. The last of the Block I modules was deployed at the three field test sites. Work was focused on the Pasadena site automatic data acquisition system, but problems remained at the end of the period.

Work performed during this and the previous quarter culminated in a number of documents that were published during this reporting period. Application of a preliminary version of the SAMICS (Solar Array Manufacturing Industry Costing Standards) Workbook showed the need for a simplified hand calculation and/or the SAMIS III computer program. "Fluidized Bed Si Deposition Process" described in-house work done in support of one of the more promising silicon production processes. The solar cell module problem/failure reporting procedure document was released and implemented, and P/FR report forms were distributed to all test and application centers.

SECTION II

PROJECT ANALYSIS AND INTEGRATION AREA

During this quarter the following activities were undertaken by the Project Analysis and Integration Area, by task:

A. PLANNING AND INTEGRATION

Planning and integration were focused on support of the ERDA Headquarters Program Planning Group in April, at NASA/LeRC, in May and June at MERADCOM/Virginia. In addition, an integration plan was formally approved by LSSA Project Management in late June.

B. ARRAY TECHNOLOGY COST ANALYSIS

1. Uniform Costing Methodology

Theodore Barry and Associates (TB&A) was selected to be the SAMICS (Solar Array Manufacturing Industry Costing Standards) support contractor to prepare standardized cost and indirect requirement data. The contract began June, 1977.

Application of the preliminary version of the SAMICS Workbook to a wafer-to-module processing sequence was completed. Several LSSA contractors reviewed the Workbook and TB&A prepared a detailed critique. The upshot was that the methodology is theoretically sound, but that hand calculations, using the preliminary version of the Workbook, were possible but not practical. Need for a simplified hand calculation procedure and/or the SAMIS III computer program was identified.

2. Industry Simulation

Refinement of the SAMIS (Solar Array Manufacturing Industry Simulation) methodology and coding of the SAMIS III computer program continued. By the end of the period, design was about 85% complete, coding about 30%.

3. Price Goal Allocation

The price goal allocation presented in Table 2-1 was developed in May, 1977. Revisions occur whenever new information permits a better definition of the goals. This is a working tool of LSSA Project management, and does not represent a commitment to any particular subsystem at this time.

Goals are set for the following items: high grade polysilicon, silicon wafers, photovoltaic cells, encapsulation materials, and complete modules. The first quantity given is the total price of the item, expressed in units natural to that item. Next is the cost of the previous process steps (if any), which is then subtracted from the total item price to

Table 2-1. Current Price Goals

		1978	1980	1982	1984	1986
High Grade Polysilicon						
Price	$/Kg	60	45	25	17	10
Contribution to Module Price	$\$/W_{pk}$	1.16	.76	.28	.135	.064
Wafers						
Total wafer price	$\$/m^2$ wafer	381	245	128	38	18.2
Cost of Silicon	$\$/m^2$ wafer	121	85	38	14	7.3
(Value added) price	$\$/m^2$ wafer	260	160	90	24	10.9
Contribution to Module Price	$\$/W_{pk}$	2.50	1.43	.67	.230	.096
Cell Fabrication						
Total cell price	$\$/m^2$ cell	719	447	228	77	41.6
Cost of wafer	$\$/m^2$ cell	476	306	142	40	19.2
(Value added) price	$\$/m^2$ cell	243	141	86	37	22.4
Contribution to Module Price	$\$/W_{pk}$	1.87	1.01	.576	.336	.187
Encapsulation Materials						
Price	$\$/m^2$ module	21	13	11	7.4	3.0
Contribution to Price	$\$/W_{pk}$	.22	.12	.09	.075	.027
Module Assembly and Encapsulating						
Total Module Price	$\$/m^2$ module	682.5	437	240	100	55.1
Cost of cells and encapsulation materials	$\$/m^2$ module	560.5	363	194	77.5	41.2
(Value Added) Price	$\$/m^2$ module	122	74	46	22.4	13.9
Contribution to Module Price	$\$/W_{pk}$	1.25	.68	.384	.224	.126
Total Module Cost		7.00	4.00	2.00	1.000	.500

All goals are expressed in 1975 dollars.

obtain a value added price. Finally the contribution of this value added price to the final system price is given, in terms of $\$/W_{pk}$. This conversion is from natural units to $\$/W_{pk}$, and includes an adjustment for subsequent process yields. Estimates for those yields are given in Table 2-1; relationships and conversion formulas are shown in Table 2-2.

C. ARRAY LIFE CYCLE ANALYSIS

Continuing progress was made toward the construction of a maintenance policy model which develops the cost implications of various maintenance actions. Specifically, exponential degradation and bathtub failure profiles have been included in the maintenance model. The implications of maintenance policy were formulated and presented in the 4th Project Integration Meeting, in May, 1977. One significant conclusion has been that the economic life of modules may require the replacement of the modules before the physical life of the modules. Under nominal assumptions on module degradation and failure the economic life of the module is about half of the physical life.

A subcontract with Bechtel Corporation to provide detailed cost relationships in support of the life-cycle cost modeling effort was being initiated. It is intended that the cost relationships be provided for several flat-plate module designs and array design approaches.

D. ECONOMICS AND INDUSTRIALIZATION

The development of a Commercialization and Industrialization Plan for the ERDA/DSE was conceptually completed and a draft completed during this period. Participants were JPL, MIT/EL and LeRC.

An energy systems economic analysis seminar was presented at the LeRC program planning group meetings which discussed the software capabilities developed by LSSA E & I Task.

Support was given to an Engineering Economic Analysis workshop sponsored by ERDA at the MITRE Corporation in the Washington area. A Technology Diffusion Study was initiated toward the end of the reporting period. The purpose of the study is to analyze the diffusion process of PV among manufacturers and to articulate potential barriers, both economic and others of an institutional nature.

Table 2-2. Conversion Formulas

Price Goal Assumptions

(I) Insolation = 1000 W/m^2
(D) Density of Silicon = 2330 kg/m^3
(u) Unit conversion: 1 mil = $2.54 * 10^{-5}$ m

			1976	1978	1980	1982	1984	1986
η_e	Encapsulated Cell Efficiency							
	Ingot		.11	.13	.14	.15	.15	.15
	Non-Ingot				.10	.105	.11	.12
η_p	Packing Efficiency							
	Ingot		.70	.75	.78	.80	.85	.90
	Non-Ingot				.90	.90	.91	.92
t	Cell Thickness (in the module) (mils)		15	12	12	10	10	10
Y_w	Silicon to wafer yield (gm wafer/gm/Si)							
	Ingot		.38	.41	.43	.45	.47	.48
	Non-Ingot				.70	.75	.80	.90
Y_{etch}	Silicon not lost through etching during cell manufacturing		.85	.86	.87	.88	.89	.90
Y_{mfg}	Cell yield from wafer to finished module	.76	.80	.80	.90	.95	.95	

Price Goal Relationships

1. High grade polysilicon:
$$\$/W_{pk} = \$/kg * (t * U * D)/(I * \eta_e * Y_w * Y_{etch} * Y_{mfg})$$

2. Wafer (Value Added) contribution to price
$$\$/W_{pk} = \$/m^2 \text{ wafer}/(I * \eta_e * Y_{mfg})$$

3. Cell fabrication
$$\$/W_{pk} = \$/m^2 \text{ cell}(I * \eta_e)$$

4. Encapsulation Materials
$$\$/W_{pk} = \$/m^2 \text{ module}/(I * \eta_e * \eta_p)$$

5. Module assembly and encapsulating
$$\$/W_{pk} = \$/m^2 \text{ module}/(I * \eta_e * \eta_p).$$

SECTION III

TECHNOLOGY DEVELOPMENT AREA

A. SILICON MATERIAL TASK

The objective of the Silicon Material Task is to establish by 1986, an installed plant capability for producing silicon suitable for solar cells at a rate equivalent to 500 megawatts (peak) of solar arrays per year at a price of less than $10 per kilogram. The program formulated to achieve this objective is based on the conclusion that the price goal can=ot be reached if the process used is essentially the same as the present commercial process for producing semiconductor-grade silicon. Consequently, it is necessary that either a different process be developed for producing semiconductor-grade silicon or a less pure and less costly silicon material (i.e., a solar-cell-grade silicon) be shown to be utilizable.

1. Technical Goals

Solar cells are presently fabricated from semiconductor-grade silicon, which has a market price of about $65 per kilogram. A drastic reduction in price of material is necessary to meet the economic objectives of the LSSA Project. One means for meeting this requirement is to devise a process for producing a silicon material which is significantly less pure than semiconductor-grade silicon; the price goal for this material is less than $10 per kilogram. However, the allowance for the cost of silicon material in the overall economics of the solar arrays for LSSA is dependent on optimization trade-offs, which concomitantly treat the effects of the price of silicon material and the effects of material properties on the performance of solar cells. Accordingly, the program of the Silicon Material Task is structured to provide information for the optimization trade-offs concurrently with the development of high-volume and low-cost processes for producing different impurity-grades of silicon.

2. Organization and Coordination of the Silicon Material Task Effort

The Silicon Material Task effort is organized into five phases. As Table 3-1 indicates, Phase I is divided into four parts. In Part I the technical feasibility and practicality of processes for producing semiconductor-grade silicon will be demonstrated. In Part II the effects of impurities and of various processing procedures on the properties of of single-crystal silicon material and the performance characteristics of solar cells will be investigated. This body of information will serve as a guide in developing processes (in Part III) for the production of solar-cell-grade silicon. The process developments in Parts I and III will be accomplished through chemical reaction, chemical engineering, energy-use, and economic studies. In Part IV of Phase I, the relative commercial potentials of the various silicon-production processes developed under Parts I and III will be evaluated. Thus, at the end of Phase I a body

Table 3-1. Organization of the Silicon Material Task Effort

Phase/Part	Objective
Phase I	Demonstrate the technical feasibility and practicality of processes for producing silicon.
Part I	Establish the practicality of a process capable of high-volume production of semiconductor-grade silicon at a markedly reduced cost.
Part II	Investigate the effects of impurities and of various processing procedures on the properties of single-crystal silicon material and the performance characteristics of solar cells.
Part III	Establish the practicality of a process capable of high-volume production of solar-cell-grade silicon at a price of less than $10 per kilogram.
Part IV	Evaluate the relative commercial potential of the silicon-production processes developed under Phase I.
Phase II	Obtain process scale-up information.
Phase III	Conduct experimental plant operations to obtain technical and economic evidence of large-scale production potential.
Phase IV	Design, install, and operate a full-scale commercial plant capable of meeting the production objective.

of information will have been obtained for optimization trade-off studies and the most promising processes will have been selected.

Phase II will be initiated to obtain scale-up information. This will be derived from experiments and analyses involving mass and energy balances, process flows, kinetics, mass transfer, temperature and pressure effects, and operating controls. The basic approach will be to provide fundamental scientific and engineering information from which valid extrapolations usable for plant design can be made; applicable scale-up correlations will also be used. This body of scale-up information will then provide the necessary basis for the design, construction, and operation of a large-scale production plant.

Since the installation and operation of a commercial chemical process plant that incorporates a new process involves high risks, experimental plants will be used to obtain technical and economic evidence of large-scale production potential. In the experimental plant phase (i.e., Phase III) there will be opportunities to correct design errors; to determine energy consumption; to establish practical operating procedures and production conditions; and to more realistically evaluate the requirements for instrumentation, controls, and on-line analyses.

In the final phase of the Silicon Material Task (i.e., Phase IV), a full-scale commercial plant capable of meeting the production objective will be designed, installed, and operated. The experimental plant and the commercial plant will be operated concurrently so as to permit the use of the experimental plant for investigations of plant operations, i.e., for problem-solving and for studies of process optimization.

Additional basic chemical and engineering investigations to respond to problem-solving needs of the Silicon Material Task will be conducted in supporting efforts. These supporting subtasks will be accomplished under contract and by an in-house JPL program.

3. Silicon Material Task Contracts

Nine contracts are in progress: three for Part I, one for Part II, four for Part III, and one for Part IV. These contracts were negotiated after careful evaluations of responses to a Request for Proposal (RFP) and of unsolicited proposals. The contracts are listed in Table 3-2. Additional contractors for subsequent phases will be selected from unsolicited proposals and from future RFPs.

4. Silicon Material Task Technical Background

The objectives of Phase I of the Silicon Material Task are as follows:

(1) Part I - Establish the practicality of a process capable of the high-volume production of semiconductor-grade silicon at a markedly reduced cost.

(2) Part II - Investigate the effects of impurities and process-steps on the properties of single-crystal silicon material and the performance characteristics of solar cells.

(3) Part III - Establish the practicality of a process capable of the high-volume production of solar-cell-grade silicon at a price of less than $10 per kilogram.

(4) Part IV - Evaluate the relative commercial practicality of the silicon-production processes developed under Phase I of the Silicon Material Task.

Table 3-2. Silicon Material Task Contractors

Contractor	Technology Area
SEMICONDUCTOR-GRADE PRODUCTION PROCESSES (Part I of Phase I)	
AeroChem Research Laboratories Princeton, New Jersey (JPL Contract No. 954560)	Si halide-alkali metal flames
Battelle Memorial Institute, Columbus, Ohio (JPL Contract No. 954339)	Si from $SiCl_4$ reduction by Zn
Union Carbide, Sistersville, W. Virginia (JPL Contract No. 954334)	Si from SiH_4 derived by redistribution process
Motorola, Phoenix, Arizona (JPL Contract No. 954442)	Si using SiF_4 reaction with metallurgical grade Si and SiF_2 transfer
SOLAR-CELL-GRADE SPECIFICATIONS (Part II of Phase I)	
Northrop Research Hawthorne, California (JPL Contract No. 954614)	Lifetime and diffusion length measurements
C. T. Sah Associates Urbana, Illinois (JPL Contract No. 954685)	Effects of impurities
Spectrolab, Inc. Sylmar, California (JPL Contract No. 954471)	Solar cell fabrication and analysis - Si slices
Westinghouse Electric, Pittsburgh, Pennsylvania (JPL Contract No. 954331)	Investigation of effects of impurities on solar cell performance

Table 3-2. Silicon Material Task Contractors (Continuation 1)

SOLAR-CELL-GRADE PRODUCTION PROCESSES (Part III of Phase I)	
AeroChem Research Laboratories Princeton, New Jersey (JPL Contract No. 954560)	Si by use of a nonequilibrium plasma jet
Dow Corning, Hemlock, Michigan (JPL Contract No. 954559)	Si from purer source materials using arc furnace processing
Monsanto Research Corp. St. Louis, Missouri (JPL Contract No. 954338)	Solar Cell Grade Si Process
Stanford Research Institute Menlo Park, California (JPL Contract No. 954471)	Si by Na reduction of SiF_4
Texas Instruments Dallas, Texas (JPL Contract No. 954412)	Plasma Process for Production of Solar-Cell-Grade Si
Westinghouse Electric Pittsburgh, Pennsylvania (JPL Contract No. 954589)	Si by plasma-arc-heater reduction of $SiCl_4$ with H_2 and alkali metals as reducing agents
COMMERCIAL POTENTIAL OF PROCESSES (Part IV of Phase I)	
Lamar University Beaumont, Texas (JPL Contract No. 954343)	Evaluate relative commercial potentials of Si-production processes developed under the Silicon Material Task

a. Processes for Producing Semiconductor-Grade Silicon.

1) Production of Si by Zn Reduction of $SiCl_4$ - Battelle Memorial Institute. The contract with Battelle Memorial Institute is for development of the reaction for the Zn reduction of $SiCl_4$ using a fluidized bed reactor as an economical means for producing Si. Based on calculations by Battelle and Lamar University, this process has the potential for a total product cost between $9.12 and $9.68/kg Si for a 1000 metric ton/year plant.

2) Production of Si From SiH_4 Prepared by Redistribution of Chlorosilanes - Union Carbide Corporation. The Union Carbide contract is for the development of processes for the production of SiH_4 and for the deposition of Si from SiH_4. The SiH_4 process includes systems for the redistribution of chlorosilanes and the hydrogenation of the by-product $SiCl_4$ to $SiHCl_3$, which can be used as a feed for redistribution. The free space reactor and the fluidized bed reactor are techniques being investigated as the means for Si deposition.

3) Production of Si by SiF_4/SiF_2 Transport - Motorola Corporation. The Motorola contract is for the development of a process for the conversion of metallurgical-grade Si into semiconductor-grade Si using the SiF_2 transport purification reaction steps.

b. Determination of the Effects of Impurities and Process-Steps on Properties of Si and the Performance of Solar Cells - Westinghouse Electric Corporation. Phase II of this contract consists of five tasks: (1) The effects of processing-steps, such as heat treatment, gettering, and crystal growth parameters, will be determined in conjunction with the impurity effects. (2) The combined effects of impurities and high B concentrations on solar cell performance will be examined. (3) The effects of impurities on n-type, P-doped Si will be determined; these data will be compared with those for p-type, B-doped Si material. (4) The impurity matrix for n-type Si will be expanded, especially in two areas: measurement and modeling for material containing two or more impurities and study of impurities which may contaminate the Si during the Si production process. (5) The effects of oxygen and carbon interactions with the impurities will be studied.

1) Production of Si Using Submerged Arc Furnace and Unidirectional Solidification Processes - Dow Corning Corporation. The Dow Corning contract is for the development of a process for improving the purity of Si produced in the arc furnace by using purer raw materials and for the further purification of the Si product by unidirectional solidification, arc furnace studies, and unidirectional solidification, and Si analysis.

2) Production of Si from Na_2SiF_6 Source Material Using Na Reduction of SiF_4 and SiF_4 Transport Processes - Stanford Research Institute. The contract with Stanford Research Institute is for the development of a two-step process for the production of Si. The steps are (1) the reduction of

SiF_4 by Na to produce high purity Si and (2) the further purification of this product by reaction with SiF_4 to form SiF_2 followed by the disproportionation of the SiF_2 to yield Si with the regeneration of the SiF_4. The work to date has dealt entirely with the first reaction.

3) Production of Si Using Arc Heater Process for Reduction of $SiCl_4$ by Na, Mg, or H_2 - Westinghouse Electric Corporation. This contract with Westinghouse is for the development of an electric arc heater for the production of Si using reactions for the reduction of $SiCl_4$ by either Na, Mg, H or Zn. The first phase consists of a review of the chemical and engineering feasibility and the designing of a system for experimental verification; it includes four subtasks: reaction analysis, plasma reactor, reactor storage and injection, and product collection and effluent disposal.

4) Production of SiH_4 or Si Using a Nonequilibrium Plasma Jet for the Reduction of $SiCl_4$ - AeroChem Research Corporation. The objective of this program is to determine the feasibility of high volume, low-cost production of high purity silane or solar-cell-grade silicon using a nonequilibrium hydrogen atom plasma jet. Reactions of hydrogen atoms in the plasma jet with chlorosilanes (added either to the discharge or to the hydrogen atom stream) are being studied.

d. Evaluation of Si Production Processes - Lamar University. The objective of this contract is to evaluate the potentials of the processes being developed in the program of the Silicon Material Task. The economic evaluations will be based upon analyses of process-system properties, chemical engineering characteristics, and costing-economics. The evaluations will be performed during all phases of the Task, using information which becomes available from the various process development contracts.

5. Summary of Progress

During this quarter the progress achieved in the individual development contracts varied considerably due to the different levels of technology-maturity; this unevenness follows the Task plan, which was structured to include efforts to demonstrate technical feasibility for comparatively immature processes along with investigations in the unit scale-up or process integration phases for process developments at the more advanced stages. Concurrently, the understanding of the effects of impurities on solar cell performance was extended as this data base was increased.

The contracts with Union Carbide and Battelle Memorial Institute are in the category of the more mature developments. The Union Carbide contract is for the development of a process for converting metallurgical grade Si into high purity Si using $SiHCl_3$ as the first intermediate, converting the $SiHCl_3$ in stages by disproportionation reactions into SiH_4, and then depositing Si from the SiH_4; free space and fluidized bed reactors are being studied as the means for accomplishing the Si-conversion. The technical

feasibility of the steps of the SiH_4 production has been demonstrated; the efforts centered on obtaining reaction-characterization data for the separate units and the design of a reactor for the hydrogenation of $SiCl_4$ to form $SiHCl_3$. The unit for disproportionation was shown to operate satisfactorily, producing highly pure SiH_4. The fabrication of the hydrogenation unit is underway. The Si-deposition work was limited to the pyrolysis investigation in the free space reactor. The product thus far is a very fine powder which must be consolidated into a dense material in order to be usable. The Si production was shown to proceed rapidly at high volume. The powder was successfully transferred and melted into rods. However, considerable contamination occurred in these early experiments, which did not adequately deal with problems of interactions with materials of construction. The next phase, to be done concurrently with the experimental program, will be the design of an integrated process-system development facility.

In the Battelle contract the present objective is to design a 25 MT/yr process-system development facility and to conduct an experiment program to support the design effort. The Battelle process incorporates the Zn reduction of $SiCl_4$ in a fluidized bed reactor. The experimental information and the design results will be used to update the plant and production cost estimates for a 1000 MT/yr production plant. The effort on the 25 MT/yr facility has progressed by the refinement of the calculations for the process flow diagram and material/energy balances. The $ZnCl_2$ electrolysis unit will be based upon a prototype fused salt cell operating at the Bureau of Mines; the design will take into account the chlorination of fine particulate Si carried over with $ZnCl_2$. The design of the integrated fluidized bed reactor/Zn vaporizer/$SiCl_4$ preheater unit is being analyzed; heat transfer calculations are being made. The experimental effort has involved (1) a study of the effects of seed particle size and bed depth; (2) the determination that the Zn vaporizer must be modified, and (3) operation of the $ZnCl_2$ electrolysis cell which revealed that no problems were introduced by the carry-over of fine particulate Si. Some of the conventional engineering design of the 25 MT/yr facility will be performed by engineering firms under subcontract.

The contract with Westinghouse Electric for the development of a process using an arc heater to provide a high temperature for the facile separation of NaCl from product Si resulting from the reduction of $SiCl_4$ by Na has proceeded through the analysis and design phase preparatory to an experimental verification effort. In this phase the subsystems for the plasma reactor, injection and storage of the reactants, product collection, and effluent disposal were considered. A final review was held in May; JPL concluded that Westinghouse had fulfilled all Phase I requirements, including the completion of the design in sufficient detail to allow the preparation of cost estimates. The analyses, however, revealed that a major problem exists in the design of the reactor in which particle growth occurs. The then-current calculation for sufficient particle growth to enable the use of a cyclone separator leads to an impractical reactor length. Analyses of alternative Si growth and collection techniques are underway. A task for Processing Engineering Analysis and Critical Design Review was added to allow for a detailed engineering analysis for a process which includes the recycling of byproducts. A design review of the verification system to be tested in Phase II was scheduled.

In the contracts with Stanford Research Institute, Dow Corning, Aerochem, and Motorola, the efforts are directed toward establishing the technical feasibility of the process being developed. In general, the studies deal with the determinations of product yields, reaction kinetics, and product purity as functions of various operation parameters. The data are insufficient for structuring process flow diagrams or for energy/mass balances.

The effects of impurities and processing on the properties of Si materials and on the performance of solar cells are being investigated in the contract with Westinghouse Electric. Studies of the low range of resistivities, of p-base materials, of compensation effects, and of an extended impurity-matrix are scheduled. The model for the dependence of solar cell characteristics on impurities is to be extended and refined. Early data allow some comparisons to be made of impurity effects in n-and p-base materials. Cu and Cr seem to have similar effects. In contrast, Mn and Ti produce much less degradation in n-base cells than in p-base cells. The model developed to describe cell performance dependence on impurity concentrations from the correlation of short circuit current and open circuit voltage with minority carrier lifetime was refined to a model correlating cell efficiency with impurity concentration. A source of uncertainty in the model is a reliable value for the saturation current, which depends on the relative contributions of the junction depletion region and the base region to the recombination of carriers. This point is being investigated further by Westinghouse and in particular in the contract with C. T. Sah Associates.

The supporting program at Lamar University (for economic analyses), at Northrop (for minority carrier lifetime and diffusion length measurements), at Spectrolab (for cell fabrication and measurement), and at the National Bureau of Standards (for the development of more sensitive measurement procedures using the neutron activation analysis and spark source mass spectrometric techniques), and at C. T. Sah Associates (for theoretical and experimental studies of the effects of impurities) continue to contribute data, information, and analyses which are needed for a comprehensive integrated Task program.

The JPL in-house supporting program consists of efforts for metallurgical and electrical measurements and for reactor studies of the pyrolysis of SiH_4 and fluidized bed operation. A report "Fluidized Bed Si Deposition Process" was published. The derived model is intended for use as the basis for improving fluidized bed reactor design and for the formulation of a research program to support contractual work in this field.

B. LARGE-AREA SILICON SHEET TASK

The objective of the Large-Area Silicon Sheet Task is to develop and demonstrate the feasibility of several alternative processes for producing large areas of silicon sheet material suitable for low-cost, high efficiency solar photovoltaic energy conversion. To meet the objective of the LSSA Project, sufficient research and development must be performed on a number of processes to determine the capability of each for producing large areas of crystallized silicon. The final sheet-growth configurations must be suitable for direct incorporation into an automated solar-array processing scheme.

1. Technical Goals

Current solar cell technology is based on the use of silicon wafers obtained by slicing large Czochralski or float-zone ingots (up to 12.5 cm in diameter), using single-blade inner-diameter (ID) diamond saws. This method of obtaining single crystalline silicon wafers is tailored to the needs of large volume semi-conductor products (i.e., integrated circuits plus discrete power and control devices other than solar cells). Indeed, the small market offered by present solar cell users does not justify the development of silicon high-volume production techniques which would result in low-cost electrical energy.

Growth of silicon crystalline material in a geometry which does not require cutting to achieve proper thickness is an obvious way to eliminate costly processing and material waste. Growth techniques such as edge-defined film-fed growth (EFG), web-dendritic growth, chemical vapor deposition (CVD), etc., are possible candidates for the growing of solar cell material. The growing of large ingots with optimum shapes for solar cell needs (e.g., hexagonal cross-sections), requiring very little manpower and machinery would also appear plausible. However, it appears that the cutting of the large ingots into wafers must be done using multiple rather than single blades in order to be cost-effective.

Research and development on ribbon, sheet, and ingot growth plus multiple-blade and multiple-wire cutting initiated in 1975-1976 is in progress.

2. Organization and Coordination of the Large-Area Silicon Sheet Task Effort

At the time the LSSA Project was initiated (January 1975) a number of methods potentially suitable for growing silicon crystals for solar cell manufacture were known. Some of these were under development; others existed only in concept. Development work on the most promising methods is now being funded. After a period of accelerated development, the various methods will be evaluated and the best selected for advanced development. As the growth methods are refined, manufacturing plants will be developed from which the most cost-effective solar cells can be manufactured.

The Large-Area Silicon Sheet Task effort is organized into four phases: research and development on sheet growth methods (1975-77); advanced development of selected growth methods (1977-80); prototype production development (1981-82); development, fabrication, and operation of production growth plants (1983-86).

3. Large-Area Silicon Sheet Task Contracts

Research and development contracts awarded for growing silicon crystalline material for solar cell production are shown in Table 3-3. This work will continue through the end of FY 1977, by which time it is expected that technical feasibility will have been demonstrated. Selection

Table 3-3. Large-Area Silicon Sheet Task Contractors

Contractor	Technology Area
RIBBON GROWTH PROCESSES	
Mobil-Tyco, Waltham, Massachusetts (JPL Contract No. 954355)	Edge-defined, film-fed growth
IBM, Hopewell Junction, New York (JPL Contract No. 954144)	Edge-defined, film-fed growth
RCA, Princeton, New Jersey (JPL Contract No. 954465)	Inverted Stepanov growth
Univ. of So. Carolina, Columbia, So. Carolina (JPL Contract No. 954344)	Web-dendritic growth
Motorola, Phoenix, Arizona (JPL Contract No. 954376)	Laser zone ribbon growth
Westinghouse Research Pittsburgh, Pennsylvania (JPL Contract No. 954654)	Dendritic web Process
SHEET GROWTH PROCESSES	
Honeywell, Bloomington, Minnesota (JPL Contract No. 954356	Dip-coating of low-cost substrates
Rockwell, Anaheim, California (JPL Contract No. 954372)	Chemical vapor deposition on low-cost substrates
General Electric, Schenectady, New York (JPL Contract No. 954350)	Chemical vapor deposition on floating silicon substrate
Univ. of Pennsylvania, Philadelphia, Pennsylvania (JPL Contract No. 954506)	Hot-forming of silicon sheet

Table 3-3. Large-Area Silicon Sheet Task Contractors (Continuation 1)

Contractor	Technology Area
INGOT GROWTH PROCESS	
Crystal Systems, Salem, Massachusetts (JPL Contract No. 954373)	Heat-exchanger ingot casting*
INGOT CUTTING	
Crystal Systems, Salem, Massachusetts (JPL Contract No. 954373)	Multiple wire sawing*
Varian, Lexington, Massachusetts (JPL Contract No. 954374)	Breadknife sawing

*Single contract provides for both ingot casting and multiple wire sawing.

of "preferred" growth methods for further development during FY 1978-80 is planned for late FY 1977 or early FY 1978. By 1980, both technical and economic feasibility should be demonstrated by individual growth methods.

An economic analysis of the Czochralski ingot growth process was performed to assess its potential to meet near-term and 1986 goals. The study was made with the intention of identifying key features of the process that are making the process costly at the present time. The analysis, conducted at JPL and elsewhere, shows that continuous growth process is the key. It was decided to solicit proposals to develop an advanced Czochralski process, specifically one achieving continuous ingot growth through multiple use of crucibles, and incorporating improved sawing techniques. These techniques, when successfully developed, will reduce costs associated with crucibles, processing, and sawing losses.

4. Large-Area Silicon Sheet Task Technical Background

a. Silicon Ribbon Growth: EFG Method--Mobil-Tyco Solar Energy Corporation. The edge-defined film-fed growth (EFG) technique is based on feeding molten silicon through a slotted die as illustrated in Figure 3-1. In this technique, the shape of the ribbon is determined by the

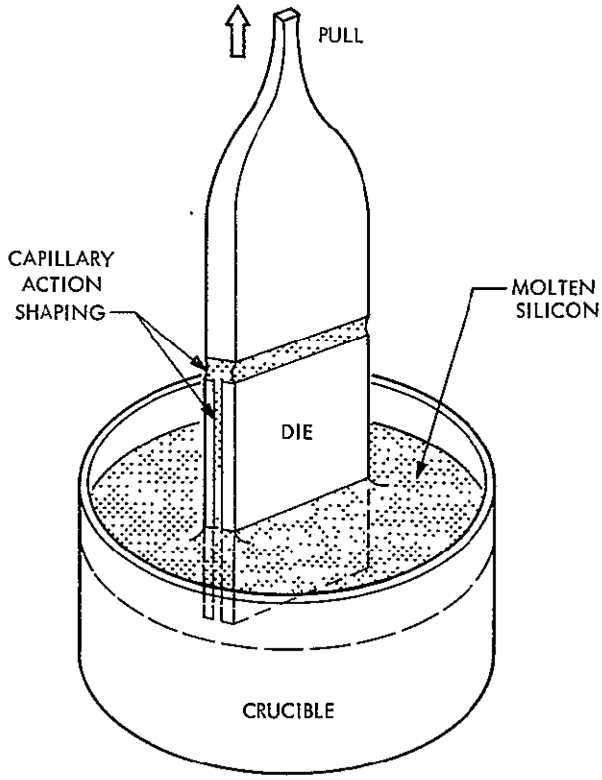


Figure 3-1. Capillary Die Growth (EFG and CAST) - Mobil-Tyco and IBM

molten silicon with the outer edge of the die. The die is constructed from material which is wetted by molten silicon (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG process to a speed of 7.5 cm/min and a width of 7.5 cm. In addition to the development of EFG machines and the growing of ribbons, the program includes economic analysis, characterization of the ribbon, production and analysis of solar cells, and theoretical analysis of thermal and stress conditions.

b. Silicon Ribbon Growth: CAST Method - IBM. The capillary action shaping technique (CAST) is based on the same principle as EFG growth (Figure 3-1); i.e., it utilizes a die constructed from material which is wetted by molten silicon. Work under this contract is directed toward evaluation of the technical and economic potential of CAST for the preparation of silicon ribbon. The effort concentrates on (1) understanding and extrapolating the effects of growth conditions, (2) characterization of the ribbon, with special emphasis on the correlation of structure and electrical performance, and (3) economic analysis of silicon growth by this and other growth techniques.

c. Silicon Ribbon Growth: Inverted Stepanov Technique - RCA. In this program emphasis is placed on developing a technique for growing ribbon-shaped silicon using a "nonwetted" die (Figure 3-2). The use of the "nonwetted" die provides the possibility of minimizing the reaction between the molten silicon and the die material. Reaction between molten silicon and wetted dies is one source of degradation in the crystallographic quality of silicon grown using a wetted die (i.e., the edge-defined film-fed growth method). The introduction of the feed from above and the growth of the single crystal in a downward direction (the inverted Stepanov technique) in part compensates for the hydrodynamic drag in the slot and for the lack of capillary rise. (The capillary rise feeds the material to the die edge in the EFG method.) The inverted geometry also leads to considerable flexibility in the growth configuration when the feed is introduced from a molten zone at the end of a solid silicon rod.

d. Silicon Ribbon Growth: Web-Dendritic Method - University of South Carolina. Web-dendritic growth makes its own guides of silicon, whereas most other ribbon processes must rely on materials other than silicon for the guides (i.e., dies) (Figure 3-3). The guides are thin dendrites that grow ahead of the sheet and support the molten silicon between them to form the sheet. The dendrite guides grow in a very precise orientation dictated by their unique growth habit. Thus the orientation of the sheet which grows between them takes on this precise orientation. The twin plane reentrant edge mechanism (TPREM) controls

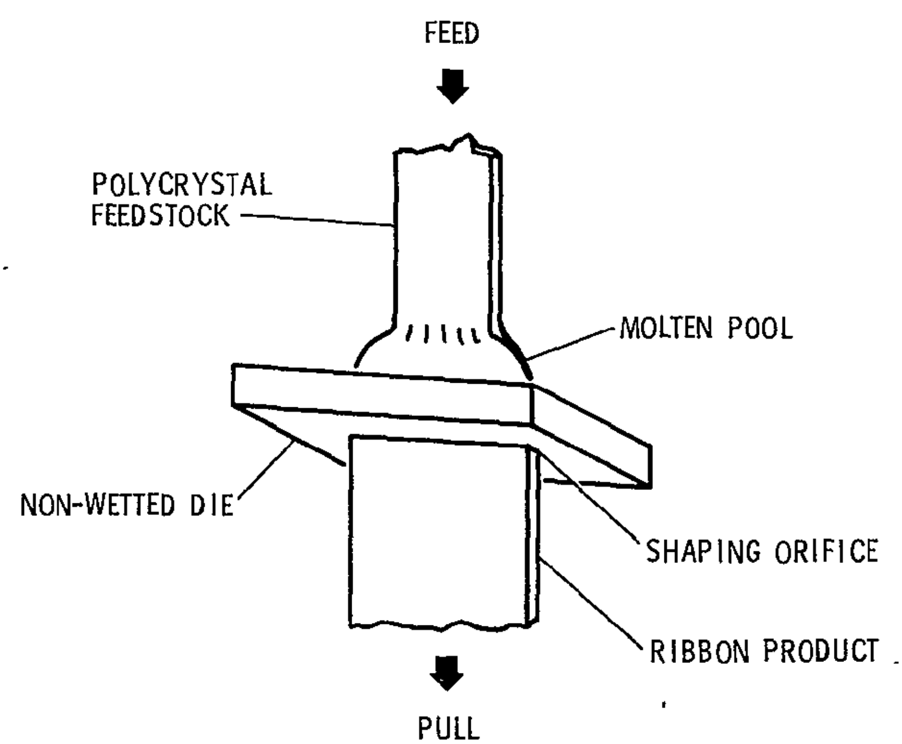


Figure 3-2. Inverted Stepanov Technique - RCA

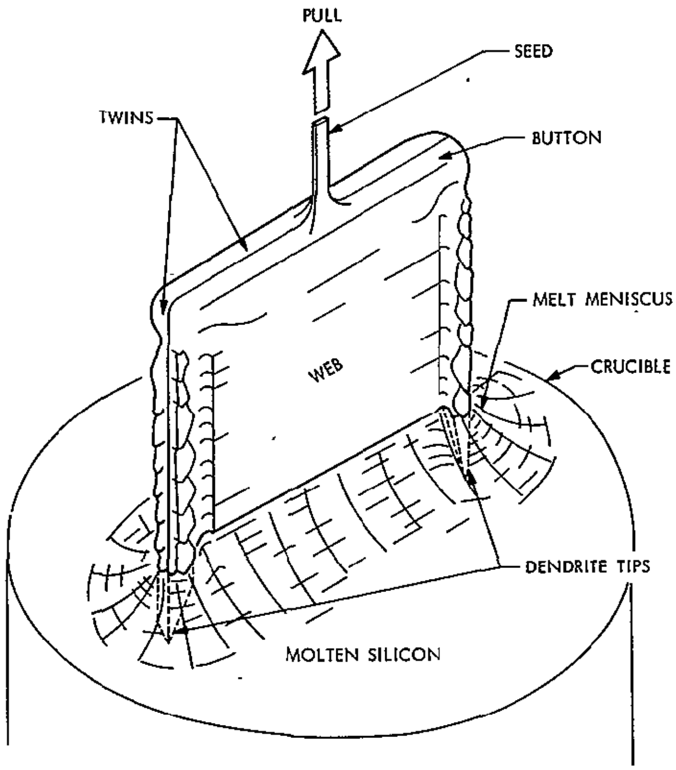


Figure 3-3. Web-Dendritic Growth - University of South Carolina

the growth of the edge dendrites, giving them their unique and internally-controlled growth direction, allowing them to grow ahead of the sheet and thus act as guides.

e. Silicon Ribbon Growth: Laser Zone Growth in a Ribbon-to-Ribbon Process - Motorola. The ribbon-to-ribbon process is basically a float-zone crystal growth method in which the feedstock is a polycrystalline silicon ribbon (Figure 3-4). The polysilicon ribbon is fed into a preheated region which is additionally heated by a focused laser beam, melted, and crystallized. The liquid silicon is held in place by its own surface tension. The shape of the resulting crystal is defined by the shape of the feedstock and the orientation is determined by that of a seed single-crystal ribbon.

f. Silicon Sheet Growth: Chemical Vapor Deposition on Low-Cost Substrates - Rockwell International. The purpose of this contract is to explore the chemical vapor deposition (CVD) method for the growth of silicon sheet on inexpensive substrate materials (Figure 3-5). As applied to silicon sheet growth, the method involves pyrolysis, or reduction, of suitable silicon compound at elevated temperature and approximately atmospheric pressure. A laboratory-type CVD reactor system with a flow-through

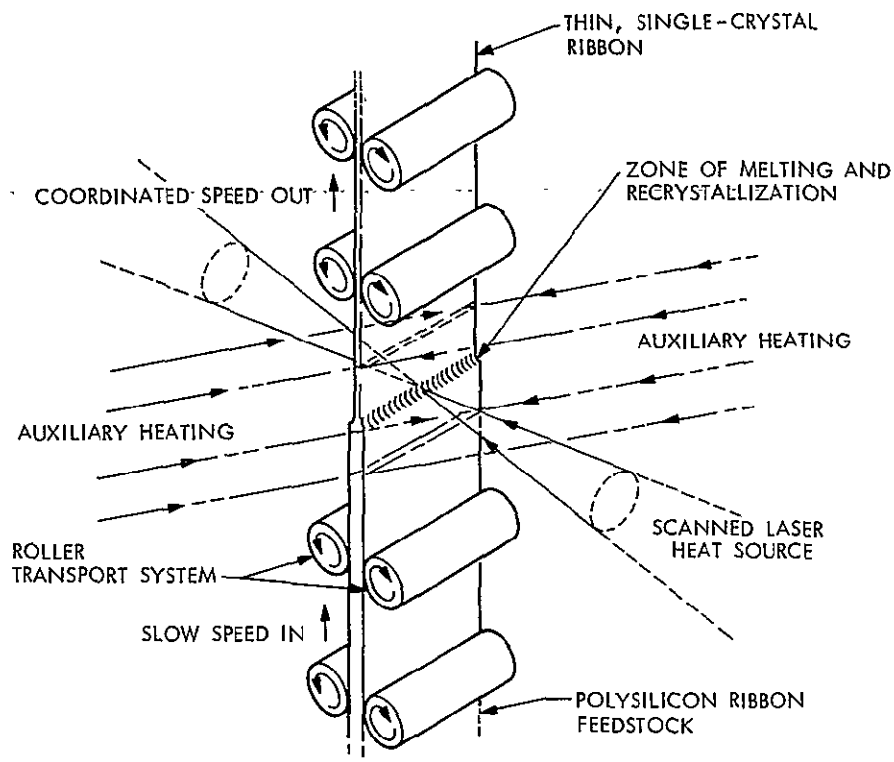


Figure 3-4. Laser Zone Crystallization - Motorola

(open-tube) vertical deposition chamber is used for these investigations. The substrate is mounted on a silicon carbide-coated carbon pedestal heated by an RF coil external to the chamber. The reactor system has been extensively modified by installation of mass flow controllers, automatic process sequence timers, and special bellows-sealed air-operated valves. This system, which has a capacity of 30 cm^2, is used as a research vehicle in an attempt to reach the goals of 100 µm grains deposited 20 to 100 µm thick on inexpensive substrates at rates up to 5 µm per minute.

g. Silicon Sheet Growth: Hot-Forming of Silicon - University of Pennsylvania. This contract is designed to determine the feasibility of hot-forming silicon in a cost-effective manner. The procedure to be followed is high-strain-rate ($\dot{\epsilon} > 1$), high-compression deformation of silicon. From this information, one can construct the hot-forming diagram for silicon and make some extrapolations of the economics of the process. The program also includes evaluations of metallurgical properties such as hot-forming texture, recrystallization texture and grain size, and of electrical properties.

h. Ingot Growth: Heat Exchanger Method - Crystal Systems. The Schmid-Viechnicki technique (heat-exchanger method) has been developed to grow large single-crystal sapphire (Figure 3-6). Heat is removed from the crystal by means of a high-temperature heat exchanger. The

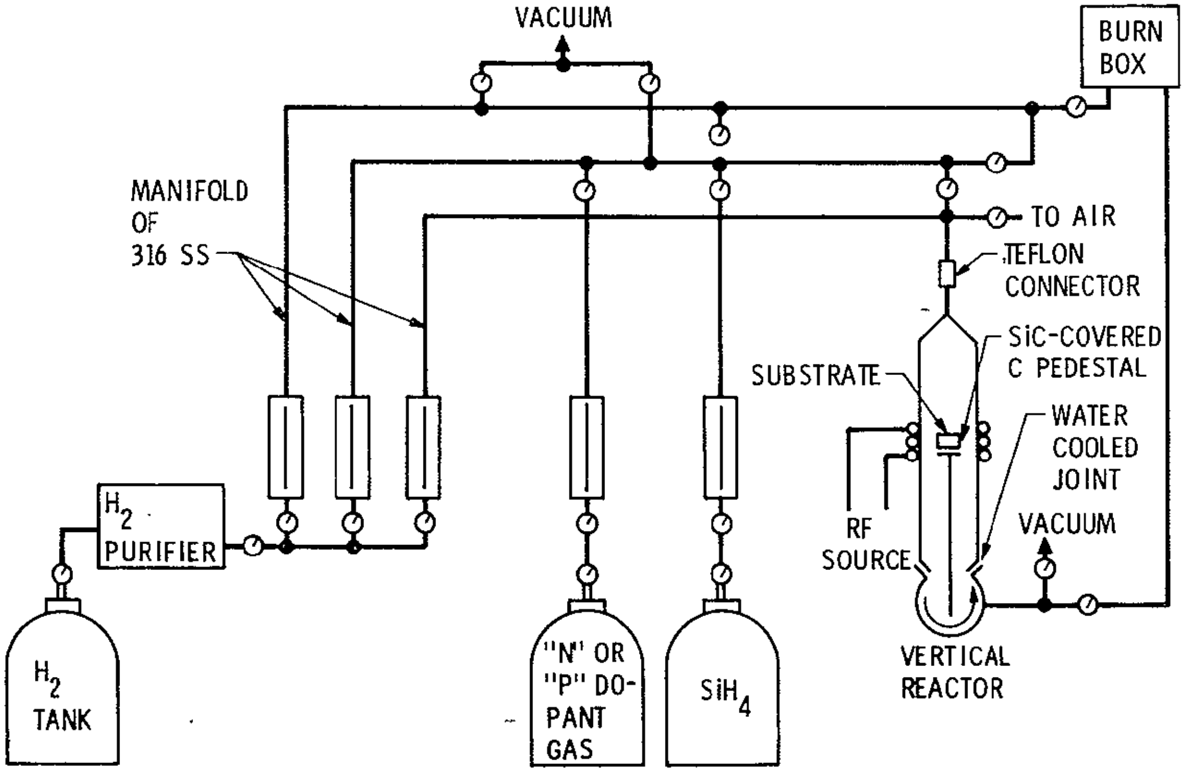
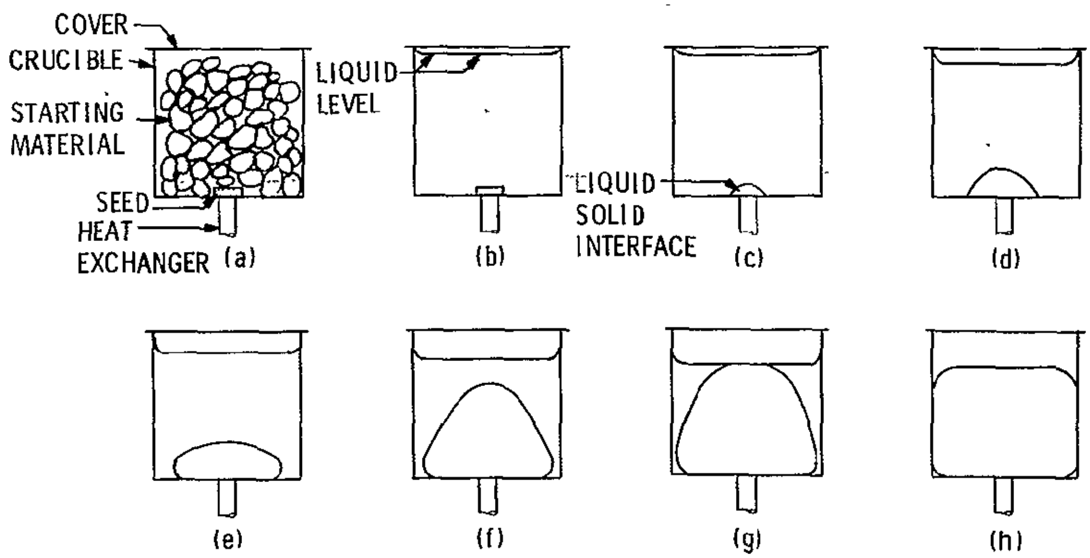


Figure 3-5. Chemical Vapor Deposition on Low-Cost Substrates - Rockwell International

heat removal is controlled by the flow of helium gas (the cooling medium) through the heat exchanger. This eliminates the need for motion of the crystal, crucible, or heat zone. In essence this method involves directional solidification from the melt where the temperature gradient in the solid might be controlled by the heat exchanger and the gradient in the liquid controlled by the furnace temperature.

The overall goal of this program is to determine if the heat-exchanger ingot casting method can grow large silicon crystals (6 inches in diameter by 4 inches in height) in a form suitable for the eventual fabrication of solar cells. This goal is to be accomplished by the transfer of sapphire growth technology (50-pound ingots have already been grown), and theoretical considerations of seeding, crystallization kinetics, fluid dynamics, and heat flow for silicon.

h. Ingot Cutting: Multiple Wiring Sawing - Crystal Systems. Today most silicon is sliced into wafers with an inside diameter saw, one wafer at a time being cut from the crystal. This is a big cost factor in producing solar cells. The lesser-used multiblade slicer can be utilized to slice silicon. The multiblade slicer has not been developed for the semiconductor industry since this method produces bow and taper unacceptable for integrated-circuit applications.



Growth of a crystal by the heat exchanger method:
(a) Crucible, cover, starting material, and seed prior to melting.
(b) Starting material melted.
(c) Seed partially melted to insure good nucleation.
(d) Growth of crystal commences.
(e) Growth of crystal covers crucible bottom.
(f) Liquid-solid interface expands in nearly ellipsoidal fashion.
(g) Liquid-solid interface breaks liquid surface.
(h) Crystal growth completed.

Figure 3-6. Crystal Growth Using the Heat Exchanger Method - Crystal Systems

The overall goal of the slicing program is to optimize multiblade (wire) silicon slicing, investigating the following parameters in particular:

(1) Rate of material removal and kerf removal.

(2) Slice thickness, wire blade dimensions, cutting forces, wire/blade tension, and other machine variables.

(3) Wires versus blades as a cutting tool.

(4) Variation of rocking motion.

(5) Introduction of abrasive during slicing operation.

(6) Effect of surface condition of tool, including consideration of hardness and method of plating.

(7) Effect of diamond abrasive particle size and type.

(8) Effect of cutting fluid composition.

The slicing operation employs a rocking motion and utilizes 50 8-mil wires. These are 6-mil steel wires surrounded by a 1-mil copper sheath, which is impregnated with diamond as an abrasive. The shape of the abrasives and their interaction with the copper and steel is an unknown variable and will be investigated. The individual wires within a multiple wire package are equitensioned by the use of a single jig in the form of a weaving machine.

The variables for slicing have been specifically identified. The independent variables are feed force, speed, rocking angle, and phase angle; the dependent variables are cutting rate, deflection, degradation of diamond, and cut profile of y versus x.

5. Summary of Progress

During this quarter, Mobil-Tyco began growing EFG cells of 11%-12% efficiency. A follow-on contract was aimed at simultaneously growing 5 ribbons, each 5 cm wide, at 7.6 cm per minute, with melt replenishment.

Motorola's RTR process is routinely growing 2.5 cm wide ribbons at 2.5 cm per minute. Design of a new RTR machine, capable of continuously growing 5-cm wide ribbons, was started.

RCA was able to achieve stable growth with the inverted Stepanov process this quarter, using graphite dies coated with CVD nitirides. The MK II growth machine was being assembled at the quarter's end. The follow-on contract was directed toward die material development.

Westinghouse came onto the contract for web growth. It began performing growth studies on the existing machine, and has completed design of its new machine.

Hot rolling of silicon into sheets suitable for solar cell fabrication, and CVD deposition of silicon sheet on ceramic substrates, did not prove to be feasible. The University of Pennsylvania was looking particularly at the recrystallization of the material after it was hot-pressed, as an economic factor. The studies showed that the recrystallization is very sluggish, and that enlarging the grain size would not be cost-effective. In the case of CVD, Rockwell International was not able to obtain grains of even 100μ, which is a necessity if the material is to be of any value at all in solar cells. Rockwell was only able to produce grain sizes of 5-10μ.

Varian has completed its work on the original Phase I contract for multiblade sawing. Using a 300 blade/spacer package, it has been able to cut 275 wafers of 250μ thick with better than 95% yield. Using a blade thickness of 150μ and a spacer thickness of 300μ, respectively, it has been able to produce a sawing yield of 22 wafers/cm length of ingot. The major limitation seems to be reducing the blade/spacer thickness. However, Varian is finding that further reduction contributes to blade instability during cutting, which results in wafer breakage and yield loss. Two new Varian machines modified for the multiblade process have been installed.

Design work on the blade alignment device and laboratory machine was started. Subcontracts were being negotiated for low-cost cutting fluid development, wafer damage studies, and solar cell fabrication.

In pursuing ingot slicing by multiwire saws, Crystal Systems has been able to cut 64 slices/in. (about 22 wafers/cm lenght of ingot) using 120μ dia. wire. The problems of uneven diamond distribution and fatigue strength of the wire appear to be the limitation.

The Task intiated the procurement of proposals for developing die materials for die-using ribbon processes and container materials; these will be substituted for the present SiO_2 and carbon dies, and the SiO_2 containers. The contracts were expected to be awarded some time during the summer. An RFP was also initiated for advanced Czochralski development, directed toward achieving semi-continuous ingot growth with continuous melt replenishment.

C. ENCAPSULATION TASK

The objective of the Encapsulation Task is to develop and qualify a solar array module encapsulation system that has a demonstrated high reliability and a 20-year lifetime expectancy in terrestrial environments, and is compatible with the low-cost objectives of the Project.

The scope of the Encapsulation Task includes developing the total system required to protect the optically and electrically active elements of the array from the degrading effects of terrestrial environments. The most difficult technical problem is expected to be developing the element of the encapsulation system for the sunlit side; this element must maintain high transparency for the 20-year lifetime, while also providing protection from adverse environments. In addition, significant technical problems are anticipated at interfaces between the parts of the encapsulation system, between the encapsulation system and the active array elements, and at points where the encapsulation system is penetrated for external electrical connections. Selection of the element for the rear side (i.e., the side opposite to the sunlit side) of the encapsulation system will be based primarily on cost, functional requirements, and compatibility with the other parts of the encapsulation system and with the solar cells.

Depending on the final solar array design implementation, the encapsulation system may also serve other functions, e.g., structural, electrical, etc. - in addition to providing the essential protection.

At present, options are being kept open as to what form the transparent element of the encapsulation system will take - glass or polymer sheet, polymer film, sprayable polymer, castable polymer, etc. The transparent element may contain more than one material and may be integral with the photovoltaic device, or be bonded to it, or installed as a window or lens remote from the device.

1. Technical Goals

Photovoltaic devices (solar cells) and the associated electrical conductors which together constitute solar arrays must be protected from exposure to the environment. Exposure would cause severe degradation of electrical performance as a result of corrosion, contamination, and mechanical damage.

In the past, test experience by government organizations and industry has confirmed that spacecraft solar arrays are poorly designed to survive the earth environment. Arrays designed for terrestrial use have shown mixed results. These results, and analyses performed as part of this task, suggest that long-life, low-cost encapsulation is possible under terrestrial conditions; however, at present, successful protection from degradation by the environment is associated with encapsulation materials and processing costs which are excessive for large-scale, low-cost use. Thus, an acceptable encapsulation system - one that possesses the required qualities and is compatible with low-cost, high-volume solar array processing - has yet to be developed.

2. Organization and Coordination of the Encapsulation Task Effort

The approach being used to achieve the overall objective of the Encapsulation Task includes an appropriate combination of contractor and JPL in-house efforts. The contractor efforts will be carried out in two phases. Within each phase some parallel investigations will be conducted to assure timely accomplishment of objectives.

During Phase I the contractor efforts and the JPL in-house efforts consist primarily of a systematic assessment and documentation of the following items:

(1) Potential candidate encapsulant materials based on past experience with the encapsulation of silicon and other semiconductor devices and on available information on the properties and stability of other potential encapsulant materials and processes.

(2) The environment which the encapsulation system must withstand.

(3) The properties, environmental stability, and potential improvement of potential encapsulant materials and processes.

(4) Test and analytical methods required to evaluate performance and predict and/or verify lifetime of encapsulant materials and encapsulation systems.

The result of this effort will then be used to specifically define additional research, development, and evaluation required during the subsequent phase.

Throughout the task atypical or unique approaches to solving the encapsulation system problem will be sought and evaluated. For example,

Phase I will include an evaluation of the feasibility of utilizing electrostatically-bonded integral glass covers as part of the encapsulation system.

In Phase II, contractor and JPL in-house efforts will be conducted to identify and/or develop one or more potentially suitable encapsulated systems and then verify the expected lifetime and reliability of these systems. Depending on the results of Phase I, the contractor effort in this phase will include an appropriate combination of some of the following items:

(1) Evaluate, develop, and/or modify test and analytical methods and then validate these methods.

(2) Perform materials and interaction testing, using these methods to evaluate candidates and demonstrate the reliability of encapsulation systems.

(3) Modify materials and processes used in encapsulation systems to improve automation and cost potential.

(4) Modify potential encapsulation system materials to optimize mechanical, thermal and aging properties.

(5) Implement research and development on new encapsulant materials.

3. Encapsulation Task Contracts

Encapsulation Task contracts are shown in Table 3-4. In addition, Professor Charles Rogers, Department of Macromolecular Science, Case Western Reserve University, serves as a consultant to this task (JPL Contract No. 954738) and will also implement selected supporting experimental investigations in the laboratories at Case.

Contractual negotiations in progress include follow-on contracts to the four major contractors, a contract with the Rockwell Science Center to study the surface characteristics of solar cells, a contract with the Motorola Solar Energy Department to investigate the feasibility of developing antireflectance coatings for glass, and a contract with Endurex of Mesquite, Texas, to study ion plating coating techniques. All of the above contracts are scheduled for execution in the third and fourth quarters of FY 1977.

In addition, considerable effort has been expended in preparing two Phase II statements of work. These are essentially complete, but may be held up pending release of the Battelle Study 4 report on life prediction methodology.

4. Encapsulation Task Technical Background

Program efforts to date have provided an assessment of the state of the art and a definition of the potential environmental and operational

Table 3-4. Encapsulation Task Contractors

Contractor	Technology Area
Battelle Memorial Institute Columbus, Ohio (JPL Contract No. 954328)	Study 1: Identification of candidate encapsulant materials based on a review of (a) worldwide experience with encapsulant systems for silicon solar cells and related devices and (b) the properties of other available materials. Study 2: Definition of environmental conditions for qualifying encapsulant materials. Study 3: Evaluation of encapsulant material properties and test methods. Study 4: Analysis of accelerated/abbreviated encapsulant test methods.
Case Western University Cleveland, Ohio (JPL Contract No. 954738)	System studies of basic aging and diffusion
Endurex Dallas, Texas (JPL Contract No. 954728)	Ion plating process and testing.
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954773)	Encapsulation coatings
Rockwell International Anaheim, California (JPL Contract No. 954458)	Experimental evaluation of accelerated/abbreviated encapsulant test methods.
Simulation Physics Burlington, Massachusetts (JPL Contract No. 954521)	Materials properties and processing
SPIRE Burlington, Massachusetts (JPL Contract No. 954521)	Electrostatically-bonded glass covers.
Springborn Laboratories Enfield, Connecticut (JPL Contract No. 954527)	Polymer properties and aging.

stresses imposed on the encapsulation system. A data base of candidate materials and their responses to these stresses is being accumulated and analyzed. Technology deficiencies are being experimentally exposed and documented.

a. Study 3: Evaluation of Encapsulant Materials Properties and Test Methods--Battelle. The experimental evaluations under Study 3 were completed during this quarter and the draft of the final report was begun. Efforts directed toward achieving the objectives of the study were broken down into several substudies encompassing both polymeric materials and glasses. Substudies identified with the letter "P" relate to polymeric materials; those identified with "G" relate to studies in which glass is a major component.

Substudy P-1: Measurement of Properties of Polymeric Materials

This study provides information on the tensile properties (modulus, strength, and elongation), thermal coefficients of expansion, moisture barrier properties, and light transmittance of candidate polymer materials in the as-received or prepared condition and after exposure to accelerated weathering (ultraviolet (UV) or thermal cycling). This information was used to help establish the aging resistance of the individual materials. The product of the tensile modulus and thermal coefficient of expansion was used, before and after aging, to estimate stress levels in materials laminates, as described by Carroll, Cuddihy, and Salama,* and indicate possible delamination at the encapsulant/cover/adhesive (or pottant) and adhesive (or pottant)/cell interfaces. Moisture barrier information was used in the selection of individual materials for use in encapsulant designs where barrier properties of the single component is critical. Light transmittance before and after environmental exposure was used to provide a measure of the utility of specific materials for cover applications.

Substudy P-2; Evaluations of Polymer Subsystems and Interfaces

Substudy P-2.1: Polymer Film Bonding. This study provided an evaluation of adhesive materials and the manner in which they are to be applied for use with the different polymer film material candidates (for the film-lamination encapsulation design), in order to reveal subsystems that are resistant to delamination and to moisture transport after test exposures to UV and to temperature cycling from -40 to 90oC.

Substudy P-2.2: Polymer Sheet Bonding. This study provided for polymer sheet candidates an output of the type described in Substudy P-2.1.

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*Carroll, W., Cuddihy, E., and Salama, M., Materials and Design Considerations of Encapsulants for Photovoltaic Arrays in Terrestrial Applications, IEEE Photovoltaic Specialists Conf., Baton Rouge, LA, Nov. 1976.

Substudy P-2.3: Cell Bonding/Sealing. This study provided an identification of adhesives and conformal coatings that are effective in protecting the metallic components of the system for moisture-induced corrosion. The effects of exposure of the materials to UV and temperature cycling are included in this substudy.

Substudy P-3: Polymer Encapsulation Systems Development and Evaluation

Substudy P-3.1: Polymer Film Lamination Design. Substudy P-3.1 provided information on candidate materials and procedures for the film-lamination type** of encapsulation design, which has significant potential for future low-cost arrays. The investigation included determination of (1) the effects of UV, humidity, and temperature cycling exposures on the output characteristics of the encapsulated cells and (2) the effects of encapsulation materials and processing on the electrical performance of encapsulated cells.

Substudy P-3.2. Polymer Sheet Bonding Design. This study provided for sheet laminates an output of the type described in Substudy P-3.1.

Substudy P-3.3. Polymer Conformal Coatings Design. This study provided for conformal coatings an output of the type described in Substudy P-3.1.

Encapsulated cells fabricated by laminating using selected films, sheets, conformal coatings, and adhesives have been prepared for evaluation before and after exposure to elevated temperature/high humidity, temperature cycling, and UV exposure. The effects of encapsulation and of aging on cell electrical performance were emphasized.

Specific cell parameters were measured in the as-received condition, after cleaning, after initial encapsulation, and after exposures to various environments (thermal cycling, UV, etc.) for a measured length of time. The parameters determined were

(1) Open-circuit voltage, V_{OC}.

(2) Short-circuit current, I_{SC}.

(3) Maximum power, P_{max}.

(4) Current at maximum power, I_{max}.

(5) Voltage at maximum power, V_{max}.

(6) Fill-factor (electrical), F.F.

**Carmichael, D.C., Gaines, G.B., Sliemers, F.A., and Kistler, C.W., Materials for Encapsulation Systems for Terrestrial Photovoltaic Arrays, IEEE. Photovoltaic Specialists Conf., Baton Rouge, LA, Nov. 1976.

(7) Series resistance, R_s.

(8) Shunt resistance, R_{sh}.

(9) Efficiency, in percent.

Because they form part of the optical path to the cell, encapsulants can affect profoundly the effective conversion efficiency of the photovoltaic module. Moreover, the service life of the cell is determined in a large measure by the choice of the encapsulant system. The critical measure of the utility of an encapsulant is its effects on the electrical output of the cells, initially and after exposure to service environments.

Short-Circuit Current, I_{sc}: With regard to the encapsulant top cover, the short-circuit current obviously is limited by how much light of the proper wavelength is allowed to reach the cell. Light can be reflected at any one of the interfaces in the optical path, it can be absorbed in the optical path, or it can be scattered in such a way that it will not be absorbed in the collection zone of the cell. In a common encapsulated-cell configuration, the optical path can consist of a top cover, an adhesive, and the antireflection (AR) coating of the cell. The amount of light reflected depends upon the index of refraction of the various layers and on their thickness. In this study, some of the encapsulant systems increased I_{sc} over that measured when the cell had only the AR coating applied (unencapsulated). That is, the indices were such that a better optical coupling was obtained. In other cases, I_{sc} decreased.

Clearly, the transmittance of the materials in the optical path also affects I_{sc}. Transmittance is a function of wavelength, and a sensitive one at some wavelength ranges for some polymeric materials. In this program, the normal transmittance was measured for some single materials. In designing the ultimate encapsulation system, the transmittance should be known for combinations of materials in the optical path, and as a function of wavelength. For composite materials especially, the diffuse and specular portions of transmittance should also be known. With such information, the "ideal" junction depth can be determined, or optical characteristics can be tailored to a given junction depth.

Open-Circuit Voltage, V_{oc}: For the ideal silicon cell, the fundamental limitation of V_{oc} is the Schottky diffusion current. V_{oc} is then a function function of I_{sc}, the dark current, and temperature. Encapsusulants might affect the junction temperature and the junction "perfection factor", A_o. They also can change the surface recombination velocity and space-charge recombination current, thereby affecting V_{oc}.

Series Resistance, R_s: An important effect the encapsulant has on the cell output is the protection, or lack of it, that the encapsulant system gives to the collecting metal grid. Grid corrosion and weakening of the metallization bond can lead to increased R_s. If the encapsulant element (adhesive, for example) interacts excessively with the AR coating-silicon interface, the collection efficiency of the junction can be decreased.

Shunt Resistance, R_{sh}: Shunting current also can be increased within the area of the cell if the interaction of the encapsulant component is

excessive. In the absence of high-temperature processes involved in the application of the encapsulant elements, the principal source of a change in shunting current is probably the degree to which the encapsulant passivates the exposed junction around the edge of the (conventional) cell. It is likely that the shunting currents can be decreased by encapsulation, which, of course, leads to a more efficient cell. The electrical conductivity of the encapsulant can also lead to a change in shunting currents, but conductivity, per se, is not likely to be a large factor in the results in this study. However, keeping water vapor away from the junction edge is, of course, an advantage.

b. Experimental Evaluation of Accelerated/Abbreviated Encapsulant Test Methods--Rockwell International. All materials degrade, however slowly, on exposure to the weather. To meet the goals of the LSSA program, solar cell encapsulants must provide protection for 20 years. Consequently, the objective of the present program is to develop methodology for making confident predictions of encapsulant performance at any exposure site in the U.S. The inherent weatherability factors of insolation, temperature, and moisture must be considered.

c. Electrostatically-Bonded Integral Glass Covers--Simulation Physics. This is a program to develop integral glass encapsulation for terrestrial solar cells, using electrostatic bonding. The feasibility of this technique has been shown and functional demonstration modules have been delivered to JPL for testing.

Electrostatic bonding is a process through which a variety of dis-dissimilar materials may be permanently joined without use of adhesives. With elevated temperature to produce ionic conductivity and an externally applied electric field to drive the mobile ions, irreversible chemical bonds are formed at the interface of the pieces being joined. The process is applicable to joining bare solar cells or those with a variety of anti-reflective coatings to glass and to joining glass to glass with the aid of inorganic interface layers. Compatibility of the process with solar cells and with associated array hardware has been fully demonstrated. Developmental modules have shown no degradation of solar cell performance caused by electrostatic bonding.

d. Polymer Properties and Aging--Springborn Laboratories. The goal of the program is to develop and test materials and encapsulation or coating processes suitable for the protection of solar cells to provide a minimum 20-year service life in a terrestrial environment. The work is being conducted at Springborn's facilities in Enfield, Connecticut, with cell performance being evaluated by Solar Power Corporation of Braintree, Massachusetts, under subcontract. The overall program is structured to include four other technical endeavors: cost analysis, selection of primers and enhancement of adhesion, upgrading ultraviolet stability, and processing repair studies.

e. Ion Plating Process and Testing--Endurex. Work under the Endurex contract began during this quarter. Endurex has developed a high-energy-level ion plating process which has proven to be a cost-effective means of applying coatings to both plastic and metallic parts. The encapsulation of silicon solar cells appears to be achievable by means of the ion plating process. Both cost-effectiveness and functional improvement are anticipated.

Since virtually any material can be deposited, the major objective of this effort will be the determination of which of several candidate materials is optimum for this application. Concurrent with the material selection will be a determination of its response to variation of parameters of the ion plating process. Bias voltage, deposition rate, and chamber pressure will have significant effects upon composition hardness and growth morphology. These will, in turn, affect such important cell parameters as active band width, antireflection, electrical conduction, abrasion resistance, thermal cycling, and environmental stability. These effects will be measured and noted.

5. Summary of Progress

During this quarter, the final report on the Battelle Study 4 was completed and published (Reference 1). Part I of the report reviews the literature for past experience on aging behavior in those material classes which are expected to be utilized as encapsulant elements, viz., glasses and polymers, and upon past experience with the design of aging tests. Part II presents the improved methodology developed in this study. The implementation of the methodology is illustrated using an example design for a solar cell module. The developed methodology emphasizes the importance of incorporating substantial contributions at the time of initiation of the test design from statisticians, materials scientists, and test engineers in order to achieve a test design that is both statistically satisfactory and is practical in terms of the number of tests to be run.

Considerations of precision, accuracy, and test sensitivity are also included in the report. It is recommended that empirical, statistical, and conceptual methods be used to analyze the data resulting from the implemented accelerated test. It is also recommended that, during the test program, predictions be made both within and between stress conditions in order to generate a "track record" for predicting degradation at lower environmental stress conditions using data obtained from higher stress conditions.

Battelle Study 5, "Evaluation of Diagnostic Methods for Use in Accelerated Abbreviated Testing" was initiated. The goal of this study is to identify suitable techniques and instruments for measuring property changes associated with the degradation of the encapsulation materials and systems. Acceptable techniques and instruments must provide sufficient measurement sensitivity and precision to allow projections of useful system lifetime, and of performance over that lifetime, from data taken under either normal or accelerated stress conditions in comparatively short time periods. Further, the measurements must provide sufficient reliability and confidence to support a selection among alternative materials and systems.

Results of the Rockwell outdoor weathering tests showed that the variation in the rate of Lexan yellowing was similar to the seasonal variation in ultraviolet intensity (based on Lexan absorbance at 360 nm). It was also shown that the cumulative UV deposited on the sample versus yellowing gives a better plot than cumulative time versus yellowing, (Reference 2). The body of data accumulated in both outdoor and accelerated exposures has allowed a variety of predictions to be made for changes in solar cell performance and encapsulant properties. These predictions will be checked against reality as future outdoor test data are received. Two mathematical models, the Weibull and the lognormal, have been useful in graphing data. These gave rather different predictions on extrapolation, so future data should allow selection of the better model.

A new program was begun at Rockwell which will consist of the fabrication, exposure, and test of approximately 150 universal test specimens (UTSs) (see Reference 3 for a description of the UTS) and various films. Nine different encapsulant systems will be tested in the UTS after exposure to both natural and accelerated weathering. The systems will include various combinations of substrate, pottant, and covers while the solar cells, copper conductors, solder bonds, and cell adhesive will be the same in all cases.

Three series of demonstration modules were scheduled for delivery to JPL for evaluation, designated Type I, Type II, and Type III. Type I modules have four 2-1/4 inch diameter cells bonded to a single 6" square sheet of 7070 glass. Cell interconnection is via evaporated films on the glass and soldered mesh between the film and the cell backs. Module backs are coated with either an RTV silicone rubber or asphalt base sealing compound. Output terminals are in the form of standard binding posts attached through holes drilled in the glass. These modules have been completed by SPIRE and evaluated by JPL. Results indicate no significant change in electrical output after electrostatic bonding or exposure to JPL standard quality control testing, including exposure to 100% RH and temperature cycling from -40oC to +90oC. Type II modules are similar to Type I modules. The major differences are a glass back, bonded to the front sheet of glass and welded rather than soldered interconnects. The back glass has a milled cavity to accept the solar cells that are bonded to the front glass. The two sheets of glass are in contact only along a quarter inch wide perimeter where an electrostatic bond permanently joins them through a silicone film. Electrical feed-throughs are accomplished through evaporated films. These modules are scheduled for completion by SPIRE in early November. Plans are being made at JPL to expose these modules to various combinations of natural and accelerated weathering. The Type III module series will be totally integral. Two sheets of glass will be completely deformation-bonded around the encapsulated cells. Interconnection will probably be by metal ribbons. Edge sealing will again be by silicone films. The necessary bonding conditions have been established and a one-cell prototype has been produced. Several problems remain to be solved before the modules can be produced.

Springborn Laboratories completed 240 days of indoor accelerated weathering on a large number of polymeric encapsulating materials. The results of optical and mechanical testing on the survivors will be reported.

Encapsulation of mini-modules (two cells per module) with various candidate systems was completed except for difficultly processed low-cost thermoplastic materials. Processing of these materials for encapsulation of modules has turned out to be an as-yet unsolved problem. Such materials are normally processsed by techniques such as injection molding which are not suitable for photovoltaic modules because of cell breakage. Various techniques such as solvent casting, plasma spraying, electrostatic powder coating, and fluidized beds have been tried without success. Because of the economic advantages of the thermoplastic materials, development of processing techniques remains a continuing effort.

Outdoor aging of candidate materials was begun at Desert Sunshine Environmental Testing near Phoenix, Arizona. These candidate materials are those showing the most promise from the Springborn indoor accelerated weathering tests previously mentioned. In addition, some mini-modules were installed for similar outdoor aging.

Work was started on a new contract at Springborn to modify existing low-cost materials, particularly thermoplastic molding materials. Modifications are for two purposes: (1) to make non-weatherable but very low-cost materials more weatherable to meet LSSA life goals, and (2) to adapt promising but difficultly processable materials to module processing requirements.

A contract with Endurex Co. of Mesquite, Texas, to investigate ion plating techniques was begun. The primary effort in this contract is to develop ultra-thin moisture barriers for solar cells. To this end, a program plan was prepared, moisture-sensitive solar cells were procured, and work begun on evaluating the hermetic capabilities of materials applied by the ion/plating process.

A research contract with Rockwell Science Center was begun. The research has focused on the aging characteristics of bonded interfaces and how these interfaces are related to failures such as delamination. A cursory evaluation of ellipsometry and Auger electron spectroscopy as techniques for characterization of encapsulant surfaces and interfaces was completed. Preliminary experiments with glass/encapsulant interfaces showed that peeling rate under constant peeling angle and force is extremely sensitive to moisture. Time compression effects induced by high-moisture environments will be studied.

A research contract with Case Western Reserve University was begun. The research work will investigate the effects of aging on the transport of oxygen, moisture, and pollutants through polymer encapsulant materials. Calibration of test equipment using polyethylene, a material with known permeability/degradation properties, have been completed. Studies have been initiated on polycarbonate and polymethylmethacrylate copolymers.

Work has continued in-house to analyze failures and degradations in modules obtained in large-scale procurements. A significant effort is being expended on the problem of soil accumulation and the development of measurement techniques.

Problems involving the cure of RTV-615 silicone rubber have also been investigated in-house. Elevated temperatures have been recommended to completely cure the RTV-615 to alleviate tackiness which is observed to persist after many months of field exposure. Where RTV-615 to RTV-615 bonding is required, a primer coat of RTV-108 (General Electric Co.) dissolved in methylethyl ketone (MEK) applied to the previously cured RTV-615 has been found effective in promoting adhesion.

SECTION IV

PRODUCTION PROCESS AND EQUIPMENT AREA

The overa... ....ve of the Production Process and Equipment Area is to develop the technology necessary to achieve high-volume, low-cost production of silicon solar array modules. The goal of this task is to develop the capability to fabricate solar array modules of 10% or better conversion efficiency at a selling price of $0.50/watt or less, at a rate of 500 megawatts per year, with a 20-year operating life. Many of the decisions that must be made during the task effort cannot be made independently and will result from trade-offs with other decisions that are made both within this task and in conjunction with other tasks of the Project.

A. TECHNICAL GOALS

The manufacture of solar cells and arrays is presently accomplished under the judgment and direct control of individual operators. Because of the limited quantities of solar cells and arrays produced, costs are high. Automated solar cell production, as proposed, will lead to significant reductions in manufacturing cost. In addition, automation will result in uniformity of cell processing with a reduction of waste due to rejected product.

B. ORGANIZATION AND COORDINATION OF THE PRODUCTION PROCESS AND EQUIPMENT AREA EFFORT

The Production Process and Equipment Area effort is divided into five phases, occurring over a 10-year period of time (Figure 4-1). The phases are

I. Technology assessment.

II. Process development.

III. Facility and equipment design.

IV. Experimental plant construction.

V. Conversion to mass production plant (by 1986).

Phase I, which was initiated in February 1976, has these specific objectives:

(1) To identify the requirements for economical manufacturing processes and facilities.

(2) To assess the technology currently used in the manufacture and assembly processes that could be applied to solar arrays.

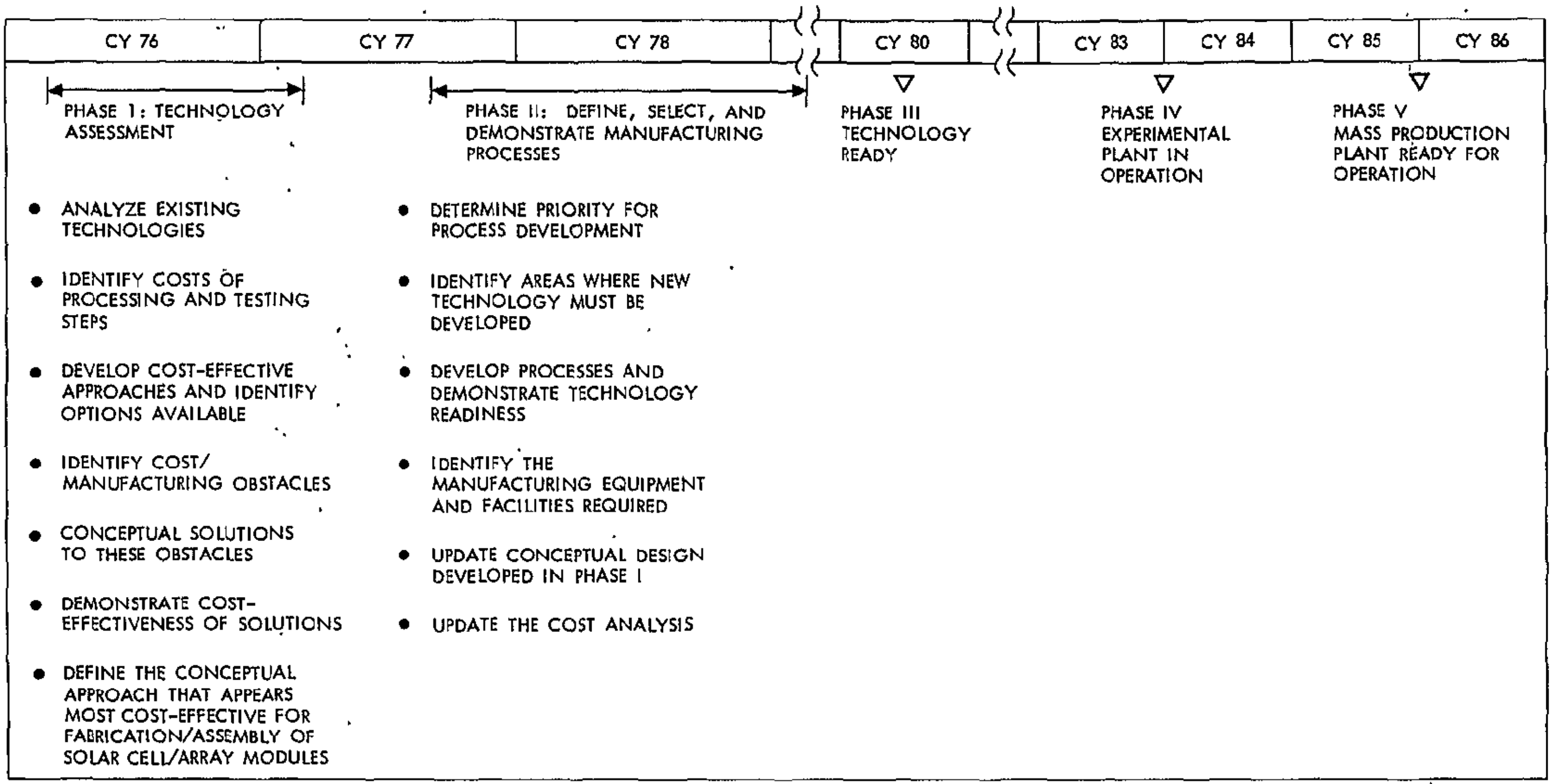

Figure 4-1. Production Process and Equipment Area Schedule

(3) To determine the level of technology readiness to achieve high-volume, low-cost production.

(4) To propose processes for development.

Contractors are shown in Table 4-1.

C. SUMMARY OF PROGRESS

1. Process Activities

Texas Instruments (TI) has shown that a textured surface reduces the need for a "good" AR coating. Figure 4-2 shows typical TI reflectance data as a funcion of incident wave-length on polished and textured surfaces. Surface texturing experiments are being performed at Sensor Technology, with the texturing process now requiring an etching time of only two minutes, versus thirty minutes previously. Surface texturing process experiments have produced 13+% AM1 efficient cells without the use of anti-reflective coatings on three to eight ohm-cm starting material.

A hexagonal cell development portion will utilize a software package for computer-controlled laser cutting of hexagonal cells. The computer program is based on cutting full hexagon cells rather than modified hexagons as intended by Sensor Technology. Modified hexagons will be incorporated later.

A laser for the laser scribing process has been delivered to Sensor Technology and is operational. Preliminary laser cutting experiments have shown that laser scribing and breaking have been accomplished without seriously degrading junction integrity and that a clean-up etch is no trequired.

Experimental and analytical work on process variables is being conducted under the Phase I extensions at Motorola, RCA and TI. Cells are being fabricated in quantity using advanced processes such as ion implantation. For some processes, an unanticipated increase in the number of recommended process steps has raised somewhat the final cost projection above previous estimates.

The most cost-effective process sequence determined by RCA to date is shown in Figure 4-3. The predicted cost of processing wafers into finished modules is $0.273/watt. The assumed yield is 81.47% with an annual production rate of 50 MW.

Table 4-1. Production Process and Equipment Area Contractors

Contractor	Type Contract	Technology Area
General Electric R & D Schenectady, New York (JPL Contract No. 954607)		Shingle Type Modules
Lockheed, Inc. Sunnyvale, California (JPL Contract No. 954653)		Module Design and Fabrication
Motorola Phoenix, Arizona (JPL Contract No. 954363)	Phase I	Manufacturing processes assessment
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954716)		Panel Development
RCA Princeton, New Jersey (JPL Contract No. 954352)	Phase I	Manufacturing processes assessment
Sensor Technology Chatsworth, California (JPL Contract No. 954751)		Hi-efficiency Panels
Simulation Physics Burlington, Massachusetts (JPL Contract No. 954655)		Module Design and Fabrication
Solarex Rockville, Maryland (JPL Contract No. 954606)		Processing energy study
Solar Technology Chatsworth, California (JPL Contract No. 954751)		Panel Development Effort
Texas Instruments Dallas, Texas (JPL Contract No. 954405)	Phase I	Manufacturing processes assessment
Texas Instruments Dallas, Texas (JPL Contract No. 954475)	Support	Large area Czochralski silicon ingot growth and wafering improvements

Table 4-1. Production Process and Equipment Area Contractors (Continuation 1)

Contractor	Type Contract	Technology Area
University of Pennsylvania Philadelphia, Pennsylvania		Automated Array
Xerox Corporation Pasadena, California (JPL Contract No. 954693)		Module Design and Fabrication

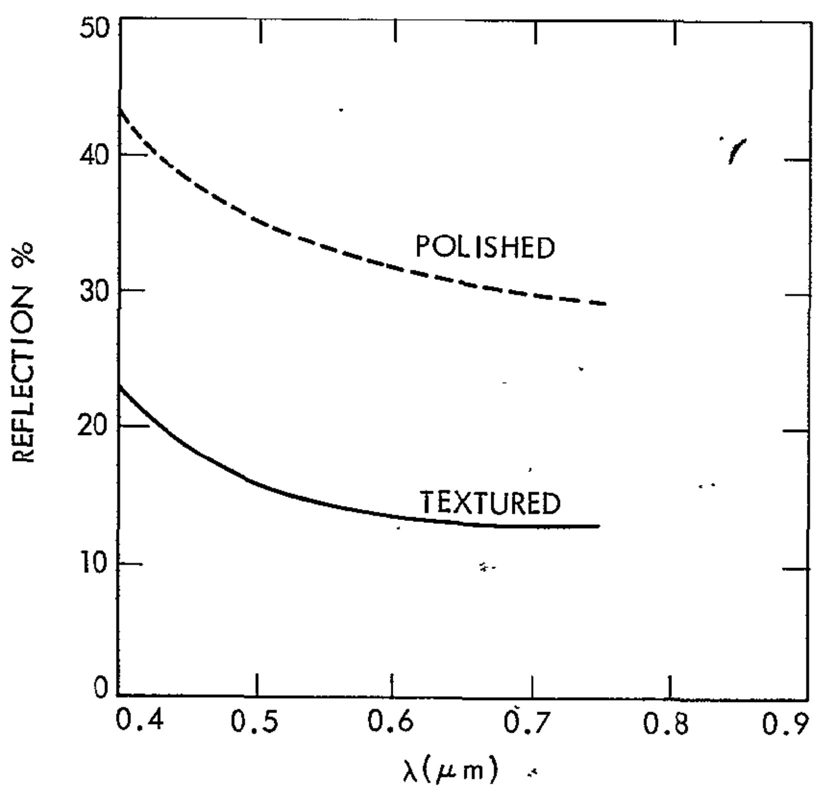

Figure 4-2. Total Reflection for Polished and Textured Surfaces

PROCESS COST OVERVIEW-$/WATT

ASSUMPTIONS: 0.717 WATTS PER SOLAR CELL AND $ 0.0 FOR 7.8 CM (3") DIAMETER WAFER

STEP	YIELD	PROCESS		MAT'L.	D. L.	EXP.	P. OH.	INT.	DEPR.	SUBTOT	SALVG.	TOTALS	%	INVEST	%
1	99.0%	SYSTEM "Z" WAFER CLEANING	(B)	0.0	0.001	0.001	0.000	0.000	0.000	0.003	0.0	0.003	1.2	0.002	0.7
2	99.0%	SCREEN PRINT SOURCE:2 SIDES	(C)	0.011	0.004	0.006	0.004	0.004	0.006	0.035	0.0	0.035	12.8	0.040	16.6
3	99.0%	DIFFUSION	(C)	0.0	0.003	0.002	0.001	0.001	0.002	0.009	0.0	0.009	3.2	0.010	4.1
4	99.0%	GLASS REMOVAL	(B)	0.0	0.001	0.001	0.000	0.000	0.000	0.003	0.0	0.003	1.2	0.003	1.3
5	99.0%	POST DIFFUSION INSPECTION:10%	(C)	0.0	0.000	0.000	0.000	0.000	0.000	0.001	0.0	0.001	0.5	0.003	1.2
6	99.0%	THICK AG METAL-BACK:AUTO	(C)	0.021	0.002	0.004	0.002	0.003	0.005	0.038	0.0	0.038	13.8	0.037	15.4
7	99.0%	THICK AG METAL-FRONT:AUTO	(C)	0.021	0.005	0.009	0.005	0.006	0.010	0.056	0.0	0.056	20.5	0.069	28.6
8	99.0%	AR COATING:SPRAY-ON	(B)	0.002	0.004	0.002	0.001	0.001	0.001	0.011	0.0	0.011	3.9	0.008	3.5
9	90.0%	TEST	(C)	0.0	0.003	0.000	0.001	0.003	0.005	0.012	0.0	0.012	4.5	0.035	14.5
10	98.0%	INTERCONNECT:GAP WELDING	(B)	0.002	0.006	0.002	0.002	0.002	0.003	0.016	0.0	0.016	5.9	0.019	8.1
11	100.0%	DOUBLE GLASS PANEL ASSEMBLY	(B)	0.072	0.002	0.002	0.001	0.001	0.002	0.080	0.0	0.080	29.2	0.014	5.7
12	100.0%	ARRAY MODULE PACKAGING	(A)	0.007	0.001	0.0	0.000	0.000	0.000	0.009	0.0	0.009	3.3	0.000	0.2
	81.4%	TOTALS		0.135	0.033	0.029	0.018	0.022	0.035	0.273	0.0	0.273	100.0	0.241	100.0
			%	49.58	12.11	10.68	6.68	7.95	13.00	100.00					

NOTE: (A)=EXISTING TECHNOLOGY; (B)=NEAR FUTURE; (C)=FUTURE ANNUAL PRODUCTION: 50.0 MEGAWATTS.

Figure 4-3. Cost Summary of Solar Cell Manufacturing Sequence Utilizing Screen Printing

The predicted manufacturing cost as a function of factory size (without the cost of the silicon material) is shown by RCA in Figure 4-4. Curve 1 depicts the cost for a 50 MW annual production; Curve 2 shows a 500 MW annual production. The financial assumptions have been made using data from a wide variety of sources, and reasonable values relfecting the general industry were assumed. This is RCA's estimate of the cost, not RCA's actual cost.

For purposes of illustration it is interesting to assume a price for the silicon material which has not been included in any of this analysis. If it is assumed that silicon wafers are available for \$20 to \$40/m^2:

	500 MW/yr	
Silicon cost	\$20/M^2	\$40/M^2
Manufacturing cost + Factory level overhead	\$0.292/W	\$0.292/W
Yielded silicon cost	0.162/W	0.324/W
Profit	0.504/W	0.05/W
	0.504/W	0.666/W

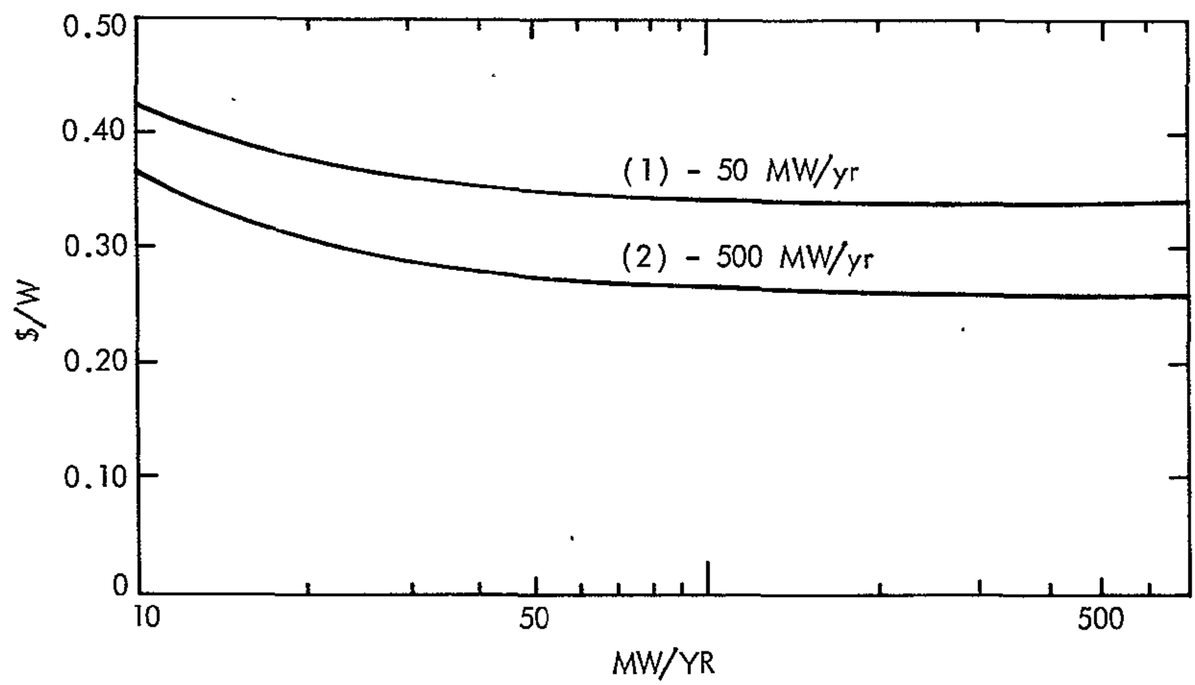

Figure 4-4. Costs of Production at 50 MW/yr and 500 MW/yr

Motorola, RCA, and TI are assessing manufacturing facilities and equipment required to achieve the 1982 interim objectives of the LSSA Project. This assessment will include the growing of Czochralski ingots and all processes involved in sequences for making encapsulated solar modules to sell at a price of $2.00/watt.

2. Assessment of Advanced Panel Design

Several weeks after the SPIRE design review at JPL, panel problems developed in the following areas: front contact adhesion, air entrapment in gel encapsulant, and module output terminal damage to back glass. All module problems were resolved. Later during this quarter, six untested and six environmentally tested panels were received from SPIRE. When the untested panels were tested at JPL, these modules passed.

In mid-May, Lockheed (LMSC) delivered the first six of twelve contractually required solar panels to JPL. Three of the panels incorporated Spectrolab cells and three incorporated OCLI cells. None of these panels were environmentally tested by LMSC. When tested at JPL, these modules passed. Later during this period, LMSC delivered six environmentally tested solar panels.

Xerox-EOS encountered minor voltage drop problems attributable to the center hole stud and push-nut configuration on its panel. Design analysis and abbreviated environmental testing of panel configuration changes have resulted in a slip in the EOS panel delivery. The unique mechanical contact design produced by Xerox is shown in Figure 4-5.

Work was progressing satisfactorily, following a design review meeting at JPL, on the fabrication of 24 R&D solar panels from Motorola.

A revised proposal to build high efficiency (>13%), long life panels was submitted to JPL by OCLI. The proposal was being reviewed at the quarter's end.

Solar Technology International was developing a module 9" x 46" with a minimum power of 20 watts AM1 utilizing low-cost aluminum p+ back contact cells with a low-cost aluminum frame.

Effort was initiated on the design of shingle-type solar cell modules from General Electric. The modules will be designed for placement on the roofs of residential homes and commercial establishments.

Effort was initiated, as an add-on to an existing NASA-funded contract, for the unique design of a module using a proprietary plastic encapsulation system, Spraylon, developed by LMSC for the space program.

Sensor Technology was developing modules of two types. The first phase has an objective of 10% AM1 modules; the second phase, 13% AM1 modules. At the end of the quarter, one module had been fabricated by the NaOH process without including the standard SiO anti-reflective coating. Measured I_{sc} increased from 520 ma to 640 ma, which is approximately 100 ma more than the I_{sc} of a standard panel fabricated at the same time.

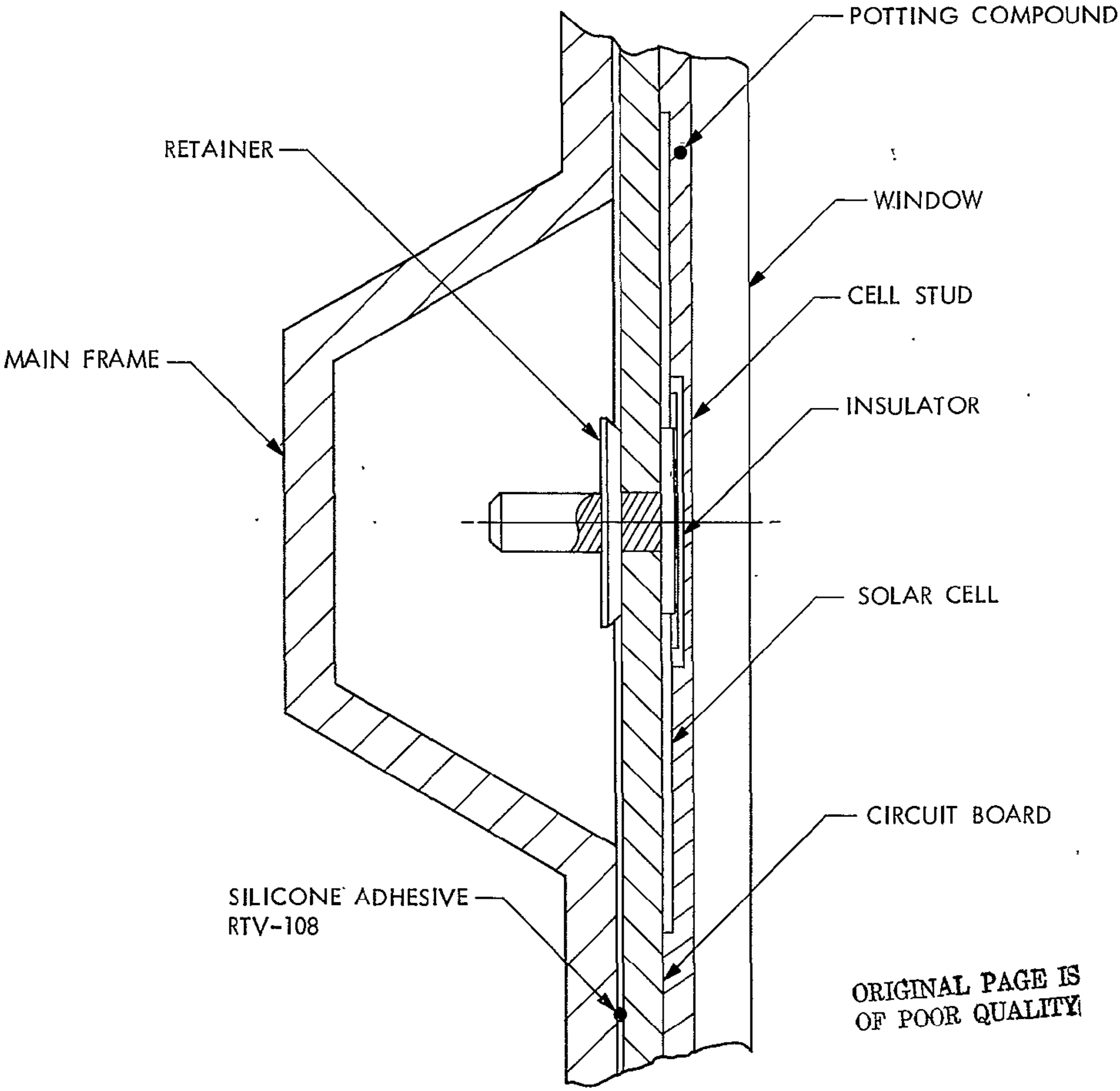

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Figure 4-5. Xerox-EOS Mechanical Contact Design

Phase II proposals for process development were received and evaluated and are currently being evaluated. The first contract placement was expected to occur by September 30, 1977.

SECTION V

ENGINEERING AREA

During the subject quarter the Engineering Area continued activities in the areas of 1) analysis and testing of solar array modules in conjunction with development of future module and array design requirements and testing methods; 2) support to the Large Scale Procurement Task for preparation and release of the Block III specification, coordination of engineering design interfaces for Block II, and problem/failure analysis activities; and 3) computer analyses and exploratory testing in support of environmental requirement generation.

Extensive work on the thermal performance of the Block I and II modules was completed during the quarter with the finalizing of the Nominal Operating Cell Temperature (NOCT) module test procedure. An arrangement with personnel at NASA Lewis Research Center has been made to provide an independent check of the accuracy and repeatability of the procedure. Documentation of the thermal performance study was in final preparation as LSSA Task Report 5101-31, "Thermal Performance Testing of Photovoltaic Modules in Natural Sunlight" (Reference 3).

Other thermal performance experiments completed during the quarter indicate that non-glass module encapsulants will accumulate enough dust to cause about a 2°C increase in module NOCT. Additional testing of opaque modules in a simulated roof mounting (backside enclosed) configuration indicates that arrays in residential applications can be expected to run about 10°C hotter (5% less power) than similar arrays with open backs. Thermal tests were also completed which have verified that fins on modules are of limited usefulness in lowering module temperature. Tests before and after machining the fins from a Block I (46 kW) module attribute the fins with lowering the module temperature only by about 3°C. A series of verification tests is continuing of module NOCTs with respect to both dust accumulation and insolation incidence angle.

The first phase of the hail (impact) test development activity was completed. Testing during the quarter was expanded to include the Block I (46 kW) modules and led to similar results as obtained for Block II (130 kW) module designs, i.e., glass modules are considerably more hail resistant than modules using silicon rubber encapsulants. (See Table 5-1). The second phase of this development is investigating damage correlations to other impact projectiles and testing procedures such as steel ball drop tests, static loading, and spring-loaded versus pneumatic guns. As shown in Figure 5-1, no correlation was found between steel ball drop tests and impact tests using ice balls, although static loading tests correlate fairly well with the ice ball tests.

An integral part of the overall hail development effort was an assessment of the hail environment and probability of a module being struck by a given size hailstone. The results indicated that the threat to modules in the Midwest region of the United States is quite severe for stones up to 2 inches in diameter. Documentation of the hail assessment study was nearing completion as LSSA Task Report 5101-45, "Environmental

5101-46

Table 5-1. Observed Hail Damage to Block II Modules

MOD* TYPE	HAILSTONE DIAMETER (in.)/VELOCITY (mph)					
	0.5/34	.75/44	1.0/53	1.25/60	1.5/65	2.0/75
A	• SLIGHT CELL CRACKING 2 of 9 SHOTS	• APPRECIABLE CELL CRACKING	• EXTENSIVE CELL CRACKING	• EXTENSIVE CELL CRACKING • DENTS ALUM PAN	• EXTENSIVE CELL CRACKING • DENTS ALUM PAN	--
B	--	NO DAMAGE	• SLIGHT CELL CRACKING 7 of 8 SHOTS	• APPRECIABLE CELL CRACKING	• EXTENSIVE CELL CRACKING	• EXTENSIVE CELL CRACKING • BENT ALUM ENCAPS. DAM • CRACKED F.G. SUBSTRATE
C	--	• WOUNDED SILICONE 1 of 5 SHOTS • SLIGHT CELL CRACKING 3 of 5 SHOTS	• WOUNDED SILICONE • APPRECIABLE CELL CRACKING	• WOUNDED SILICONE • EXTENSIVE CELL CRACKING	• WOUNDED SILICONE • EXTENSIVE CELL CRACKING	• WOUNDED SILICONE • EXTENSIVE CELL CRACKING • PUNCTURED F.G. SUBSTRATE FRAME
D	--	NO DAMAGE	NO DAMAGE	• NO DAMAGE 2 SHOTS MIDDLE • BROKE GLASS 1 of 3 SHOTS NEAR EDGE	• NO DAMAGE 3 SHOTS MIDDLE • BROKE GLASS 2 of 4 SHOTS NEAR EDGE	--

*NOTE: Encapsulant Systems By Module Type:

A: Silicone Rubber w/ Formed Aluminum Pan Substrate
B: Silicone Rubber w/ Polyester F.G. Substrate (Frame Supported)
C: Silicone Rubber w/ One-Piece Molded Polyester F.G. Substrate
D: Glass Front (PVB laminate)

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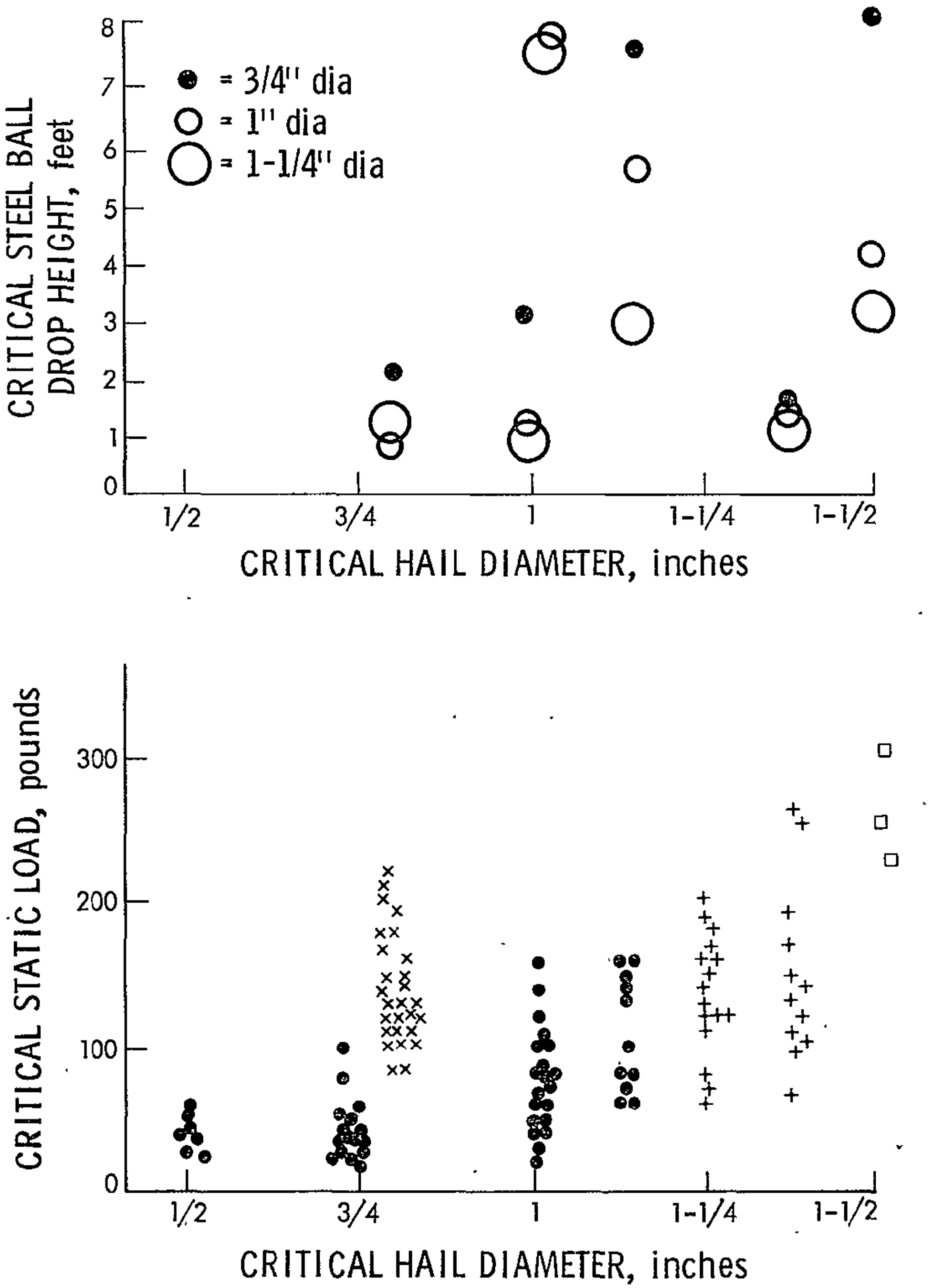

Figure 5-1. Correlation of Hail-Induced Damage with Damage Due to Dropped Steel Balls and Static-Loaded Steel Balls

Hail Model for Assessing Risk to Solar Collectors", (Reference 4). An assessment was also been carried out of the availability of appropriate instrumentation for hail monitoring. Several instruments were identified for possible incorporation into selected photovoltaic applications and test sites in high hail probability areas.

Exploratory testing of modules under conditions of high humidity with bias voltage application was initiated in an attempt to determine if the presence of an applied potential can produce early identification of ion migration/galvanic corrosion or other potential related failure modes. Initial testing was complicated when a wide variation was encountered in solar cell shunt resistance to reverse voltage between cells of different manufacturers and within a given module. Figure 5-2 indicates the spread in cell shunt resistance within a single module for each of the Block II manufacturers.

In support of developing mechanical design criteria for further arrays and modules, a variety of possible design configurations were subjected to detail structural analysis. Structural analysis of glass modules has pointed out a difficulty in determining the optimum material thickness for a given module loading. Conventional "small deflection" analytical techniques were found to be overly conservative, necessitating the use of non-linear, large-deflection analytical and empirical techniques. Experimental testing of glass module stresses was initiated.

Compilation of industry comments on the preliminary module specification 5101-16, "Silicon Solar Cell Module Design, Performance and Acceptance Test Requirements" and its supporting documentation was accomplished. The critique by a cross-section of photovoltaic module manufacturers and users indicated a positive response, especially to the move toward mounting standardization and provisions for increased design flexibility. A summary presentation of the results of the critique is included in the documentation of the 7th Project Integration Meeting (Reference 5).

Documentation of module efficiency definitions and efficiency characteristics of the Block I and II modules proceeded during the quarter and will be published as LSSA Task Report 5101-43, "Module Efficiency Definitions, Characteristics and Examples", (Reference 6).

The final report of the Bechtel Corp. study contract to assess module interface requirements with respect to installation and maintenance considerations was completed and released in June: "Engineering Study of the Module/Array Interface for Large Terrestrial Photovoltaic Arrays", (Reference 7).

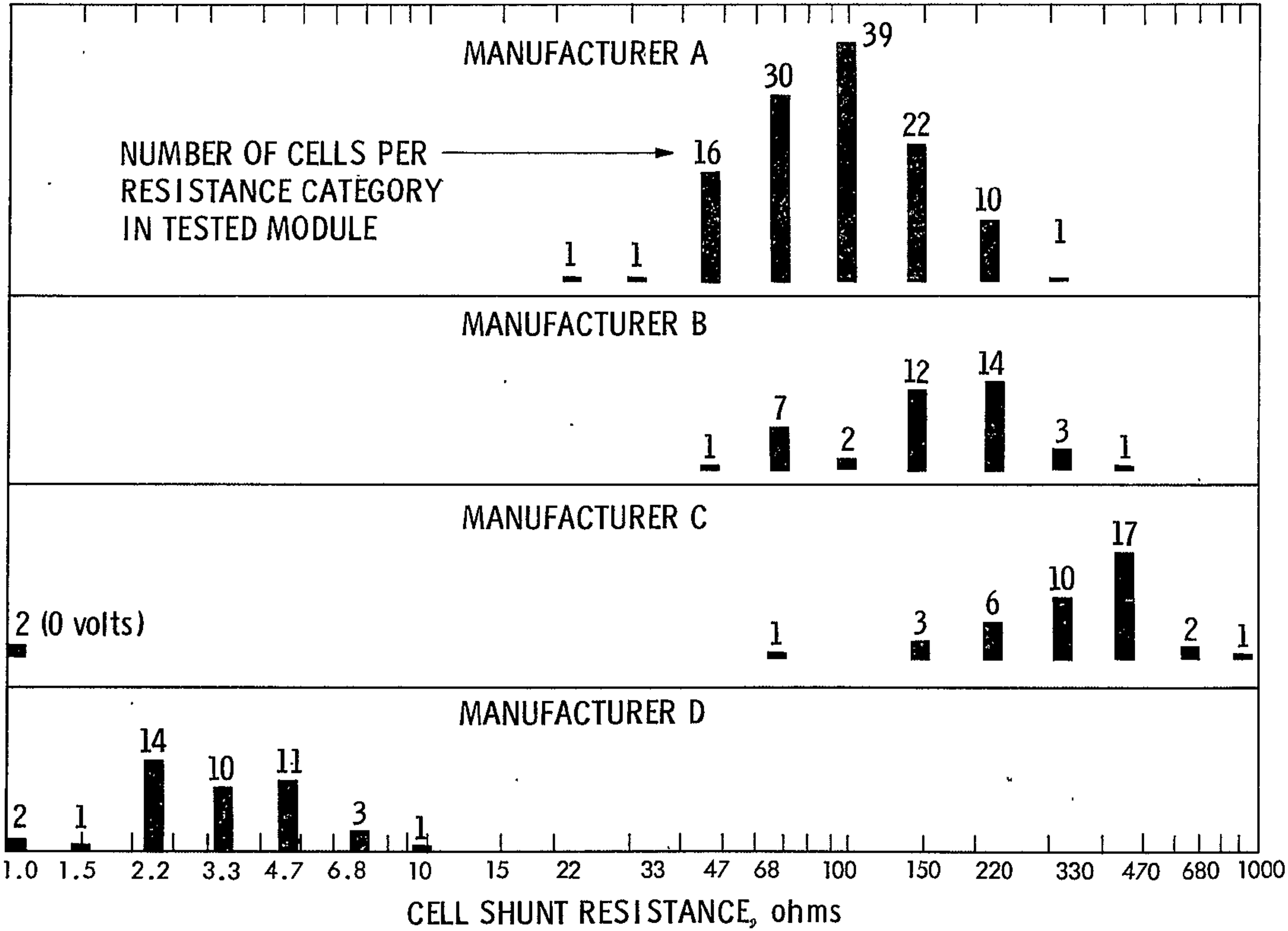

Figure 5-2. Cell Shunt Resistance for Block II Modules

5101-46

SECTION VI

OPERATIONS AREA

A. SUMMARY OF PROGRESS

Three months of production experience with the Block II (130 kW) procurement yielded the following observations: a) The manufacturers were unable to meet their delivery schedules, despite significant pressure to do so; b) 100% source inspection rejected about 20% of the modules for defects, and c) validation of acceptance criteria awaits the data from the test and applications programs. The Block III RFP for up to 200 kW of modules designed to the same specifications as those procured under Block II was reviewed and approved by JPL management during this quarter.

Several recurring defects were noted in production modules. The most common problems were 1) inadequate electrical bonding between elements of the module framework, 2) failure of the encapsulant to adhere to terminals, substrates, cells, and to other layers of encapsulant, and 3) cracking of solar cells in the module. Extensive environmental testing was performed during this period; the results are summarized in Table 6-1 of Section B.

Field testing during this quarter focused on trouble-shooting the Pasadena site data acquisition system. Several deficiencies were corrected, but by the end of the quarter the dynamic load, which is a key element, was still not functioning properly. All of the Block I modules had been deployed at the three test sites -- 136 at JPL and 46 each at Table Mountain and Goldstone -- for a total of 228 modules deployed; 58 Block II modules had been installed at the three sites by the end of the quarter. A letter requesting the use of a small piece of land at the Coast Guard's Point Vicente station had not yet been answered at the end of the quarter.

An additional 50 2 x 2 cm reference cells were received from three manufacturers, were tested at JPL, then shipped to LeRC to be used for new intermediate standards. Initial measurements showed unsatisfactory correlation between new red/blue filters installed at JPL and LeRC, but the problem was located and will be corrected.

The solar cell module problem/failure reporting procedure document (5101-26) was released and implemented in May. This document and Problem/Failure Report (P/FR) forms were distributed to all test and application centers, and P/FR reporting and analysis begun.

B. EXPANDED NARRATIVE OF ACTIVITIES

1. Large-Scale Production (LSP) Task

During this quarter, three out of the four contractors for the Block II (130 kW) procurement came up to full production and the fourth started its production run. One contractor, Solar Power Corporation, completed delivery. A summary of the schedule and deliveries for the contractors is shown in the following table.

Manufacturer	Total to be Delivered kW	April-June Shipped kW	Total Shipped to Date kW	% Complete
Sensor Technology, Inc	40	16.5	19.4	48.5
Solar Power Corp.	15	14.1	15.0	100.0
Solarex	30	17.7	18.2	60.6
Spectrolab, Inc.	40	0.0	0.7	1.7
	125	48.3	53.3	42.6

Of this production, a total of 33 kW was delivered to MIT/LL to be incorporated in the agricultural pumping applications test in Nebraska. Sample modules from each one kilowatt of modules produced were tested at JPL to assure the continued adherence to the requirements imposed upon the contractors.

Several significant defects in the modules as produced have occurred with sufficient regularity as to require some corrective action. These defects in design or processing became evident only after entering production, which supports the need for a closely monitored production experience. Three of these defects include (1) an inadequate electrical bonding between elements of the module framework, (2) several examples of failure of the encapsulant to adhere to terminals, substrates, cells, and to other layers of encapsulant, and (3) cracking of solar cells in the module.

A number of observations can be drawn from the Large-Scale Production Task (LSP) Block II after these three months of production experience.

1. Three of the four contractors have not been able to meet their scheduled deliveries, although one contractor completed his production run in three months rather than the four months planned. So, planning is not particularly accurate, which may be a characteristic of an immature industry.

2. The quantity of modules delivered per week fluctuated as much as ± 100% from the average weekly production of one vendor to ± 18% for the most consistent producer. During this period, there was significant pressure for all producing contractors to deliver according to plan.

3. Production is still subjected to 100% source inspection, which rejects about 20% of the modules submitted for various defects.

4. Validation of acceptance criteria awaits the data from the test and applications programs.

The Block III request for proposal was prepared and approved through the JPL system during this period. This procurement is for up to 200 kW of modules designed to the same specifications as those procured under Block II. Competition in the procurement is expected to be broadened to include all contractors who have designed modules to the Block II specification under contract to JPL.

2. Environmental Testing

The environmental test load at JPL increased considerably during this quarter, due to (a) Qualification testing on PP&E Area developmental modules. Three types have been received to date, and two of these have so far been subjected to temperature cycling. (b) Production samples (one per kW) from the LSP Task. Qual tests will be performed at JPL on about 130 of these Block II modules as resources permit.

A second outside testing laboratory (General Dynamics, San Diego) has been placed under contract, but facility limitations continue to slow the test effort. No chambers of adequate size are currently available at JPL, but orders have been placed for three combined environment chambers.

Table 6-1 summarizes the results of testing the Large-Scale Production modules. In addition to qualification testing, exploratory humidity-freezing and salt fog testing was carried out on modules from three of the LSP suppliers with no significant resultant degradation. Manufacturer "V" Type production modules were the subject of considerable special testing:

a. Minor solder cracks were observed on some modules at the connection of the cell string to the terminal posts. A test was designed to determine if these cracks would propagate. Temperature cycling was accelerated at 200°C/hour for 143 cycles followed by mechanical integrity (flexing) for 5357 cycles. Macrophotographs preceded and followed each step. Although extensive cell cracking resulted, no propagation of the solder cracks was detected.

b. Early production modules showed a crack in the aluminum pans at one of the stiffening ribs. These cracks, which were the result of the forming die irregularities, varied up to 7 cm in length. Eight modules were subjected to 8643 mechanical integrity cycles to verify suitability for field use. Crack measurements preceded and followed testing, using a penetrant dye. No propagation was observed.

c. After temperature cycling of the first 1 kW production samples, all eight modules in the subarray had cell cracks. Some were quite severe, and all were generally located over the stiffening ribs where the encapsulant layer is deeper, indicating that differential thermal expansion was the cause of the stress. Four modules of modified design to eliminate this problem have been received.

Table 6-1. Large-Scale Production Task Module Testing

Vendor	Number Modules	Type	Test	Results: Elect. Degrad.	Results: Physical Changes
V	4	Production	Hum-freez.	OK	Some delamination, discoloration.
V	4	Production	Salt fog	OK	Mounting bosses corroded.
V	8	44-cell prod.	T-143 (200°C/hr) and MI-5357	Severe	Overstress test to determine effect on solder cracks at terminals: no effect. Extensive cell cracking.
V	8	44-cell prod.	MI-8643	Not Measured	Test to determine if aluminum pan stiffener rib cracks would propagate: no propagation.
V	8	44-cell, glass cover	Qual.	OK	Moderate delamination all modules, especially at corners. Some discoloration.
V	8	1 kW prod. samples	Qual.	1 - 15% 1 - 5% 1 - 9% 4 - OK	All modules had cell cracks -- 13, 5, 1, 3, 8, 4, 7, and 5, respectively. Some delamination.
Y	4	Prototypes	Hum-freeze.	OK	Some delamination.
Y	4	Prototypes	Salt fog	OK	Bosses rusty.
Y	8	1 kW samples	T-50	OK	Satisfactory.
Z	3	Prototypes (no cell cement)	Qual.	OK	Delamination and several cracked cells (center module).

Table 6-1. Large-Scale Production Task Module Testing (Continuation 1)

Vendor	Number Modules	Type	Test	Results: Elect. Degrad.	Results: Physical Changes
Z	3	Prototype	Hum-freez.	OK	Satisfactory.
Z	3	Prototype	Salt fog	OK	Satisfactory.
Z	3	1 kW samples	T-50	OK	Some encapsulant delamination.

NOTES: Qual = qualification test -- 50 temperature cycles, then 5 humidity cycles and then 100 mechanical integrity (wind simulation) cycles.
T-XXX = temperature cycling - number of cycles
MI-XXXX = mechanical integrity test - number of cycles.

V-Type development modules with glass covers were also qual tested. No cell cracking resulted, but encapsulant delamination was more severe than noted previously.

There was no activity on W-type modules, but one hundred cells with evaporated contacts were humidity and temperature tested. Results indicated very little electrical degradation.

Tests of Y-type 1 kW sample modules showed very little degradation after 50 temperature cycles.

A fourth set of three Z-type prototype modules was tested this quarter. These were assembled without using cement to secure the cells to the substrate. Several cracked cells and some delamination appeared in the center module in the subarray. Because the center module had evidenced similar results in three out of four previous subarrays, a fifth subarray was built up and exposed to normal handling and transportation to determine if these environments were the cause. The results were negative. A later qual test of production samples revealed no cell cracking after temperature cycling.

Table 6-2 summarizes test data from Automated Array Assembly Task (A^3 Task) module testing. Electrical degradation was negligible, but delamination was present in a majority of modules.

Table 6-2. Module Testing A^3 Task Experimental Modules

Vendor	Number Modules	Test	Results: Elect. Degrad.	Results: Physical Changes
S	4	T-50	OK	Separation of encapsulant at edges of module -- all modules. Has appearance of elongated bubbles or cracks in encapsultant.
T	4	T-50	OK	Delamination at cells (2 of 4 modules). Five each of two solar cell types tested.

3. Field Testing

The main activity this quarter centered around the Pasadena site data acquisition system. The system was delivered on May 26, and about a week later the floating point processor was installed. During the shakedown period it was discovered that some of the components were malfunctioning. Several of these deficiencies were corrected, but at the end of the quarter the dynamic load, which is a key element, was still not functioning properly.

Wiring for the system progressed on schedule. At the end of June, all the boxes and wireways for the first 15 stands were installed. These stands will contain all of the Block I and II modules. The wiring should be complete by mid-August unless there is a delay in obtaining the necessary materials.

Considerable progress was also made in implementing the software. A comprehensive Software Requirements Document was generated which contains a detailed master plan of the software that will be incorporated into the system. Immediately after delivery of the system implementation of this software into the PDP 11/34 was started. The capability began to exist to interrogate and obtain I-V curves from modules, and by early July a graphics option for displaying an I-V curve on the CRT will exist. As part of the shakedown process 13 modules, including at least one module of each kind from Block I and II, were connected to the data system. Data were taken to obtain experience with the system and pinpoint instrument problems, and also to obtain basic information which will be used to perform temperature and light intensity corrections. Figure 6-1 shows a typical I-V curve obtained by the system. Work was continuing to implement and improve the on-site graphics capability.

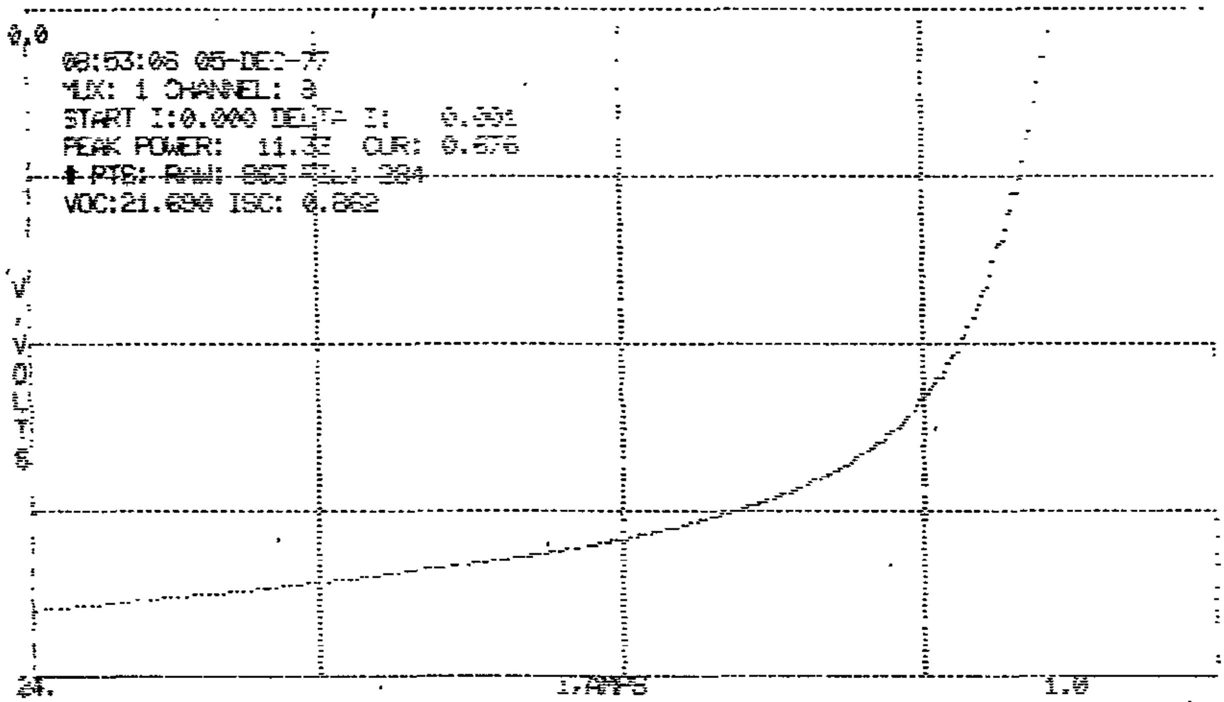

Figure 6-1. Typical I-V Curve Produced by Pasadena Field Test Site Automated Data Acquisition System

Meanwhile, site development and module deployment continued. All of the Block I modules were deployed at the three sites. All together there are some 228 modules deployed, 136 at JPL and 46 each at Table Mountain and Goldstone. Deployment of the Block II modules was proceeding as fast as they are received. At the end of June, a total of 58 had been deployed at the three sites.

A letter requesting the use of a small piece of land at the Coast Guard's Point Vicente station in the Palos Verdes Peninsula, (30 miles south of JPL) for a fourth site was sent to the commanding officer. No response has been received during the quarter. If it is approved, plans call for that site to be similar in capacity to Table Mountain and Goldstone.

4. Performance Measurements and Standards

An additional fifty 2 x 2 cm cells for reference cell production were received from all vendors except Spectrolab. The cells were measured and characterized at JPL, and forty from each lot were then shipped to LeRC. From these new cells, new intermediate standards will be generated. The need for new intermediate standards arose when a cell holder design defect was discovered that causes the existing standards to be susceptible to delamination of the quartz cover. Replacement of the standards now in use in the Block II procurement with new standards using the redesigned

package will be performed in conjunction with comparison measurements to insure that perturbations in module measurements do not occur. These replacement activities will be performed during the next quarter.

New red/blue filters have been received and installed at both JPL and LeRC. Initial measurements indicate that correlation of data between the two facilities is still unsatisfactory. The difficulty has been traced to a difference in operating voltage of the lamps in the two large-area pulsed solar simulator (LAPSS) facilities. Module measurements are not affected but red/blue ratios will require operating the facilities at identical lamp voltages for direct comparisons. The round robin experiments currently scheduled for next quarter will be used to clear up this discrepancy.

A Carson solar tracker facility is being temporarily installed at the Pasadena field test site and should be operational in July. The procurement of a second LAPSS system has been initiated. The current plan is to integrate the two LAPSS systems into a central data processing facility which will allow maximum speed and flexibility of data outputting to be realized. The hardware for automatic calibration of the LAPSS system is almost complete and will be installed next quarter.

5. Failure Analysis

The solar cell module problem/failure reporting procedure document (5101-26) was released and implemented in May. This document and Problem/Failure Report (P/FR) forms were distributed to all test and application centers. Reports are now expected from DOD, LeRC, and MIT/LL in addition to those generated by JPL environmental and field test activities.

During this quarter, problem/failure reporting and analysis occurred as outlined in Table 6-3 for Block I, II, and special Automated Array Assembly Task module testing.

The Block I failure analysis showed problems with interconnects and contacts to cells for all vendors. A manufacturer "V" module failure in JPL field test resulted from an unsoldered contact to the bottom of a cell which failed in an open circuit intermittent condition. Another module became open-circuited after the back metal separated from the silicon at the point where the interconnect was soldered; this module also failed in the JPL field test.

Block I "W" modules analyzed for electrical degradation after humidity testing were found to have silicon-to-contact problems, with an increase in series resistance causing a decrease in module power output.

Two Block I "Y" modules experienced failures in a DOD water purification test at Fort Belvoir, Virginia. The failures were attributed to contact metallization on the back of a cell that showed very poor adhesion to the silicon. Figure 6-2 shows the area under the back of the cell at the interconnect.

Table 6-3. Summary of P/FR Activity

Manufacturer	Procurement	New P/FRs	Closed P/FRs	Environmental Test	Field Test	Application Centers
"V"	Block I	2	4	5	1	
	Block II	20	3	22		1
"W"	Block I	1	15	14	1	
	Block II		3	3		
"Y"	Block I	2				2
	Block II	2	2	2		2
"Z"	Block I	2	2		2	2
	Block II	6		6		
"S"	Special	6				

Table 6-4 shows the problem category for the problem/failures reported in Table 6-3.

Two Block I "Z" modules also experienced failures in the same application. These failures were caused by fractured interconnects, which in turn caused heating, arcing, and ignition of the substrate and encapsulant material. The fractured interconnects occurred because of inadequate stress relief. Figure 6-3 shows the damaged surface of the cell and substrate.

Block II problem/failure analysis was performed on "V" modules, which suffered cracked cells after environmental testing. The problem was caused by expansion of encapsulant contained in the reinforcing grooves of the substrate under the cells. Studies are in process to improve the design.

Numerous Block II "Y" modules were found to have an intermittent contact between the junction box and the frame caused by an improperly secured mechanical fastener. This fault gave the impression of a dielectric breakdown between the solar cell and the mounting frame.

Table 6-4. Breakdown of P/FR's By Problem Cause

Manufacturer	Electrical	Mechanical	Materials	Comments
"V"	2	21	17	Cracked cells caused by differential thermal expansion of materials
"W"	18			Electrical degradation
"Y"	4	4	2	Open circuit caused by interconnect failures & intermittent grounding
"Z"	3	4	3	Electrical degradation open circuit
"A"			6	Encapsulation separation & discoloration

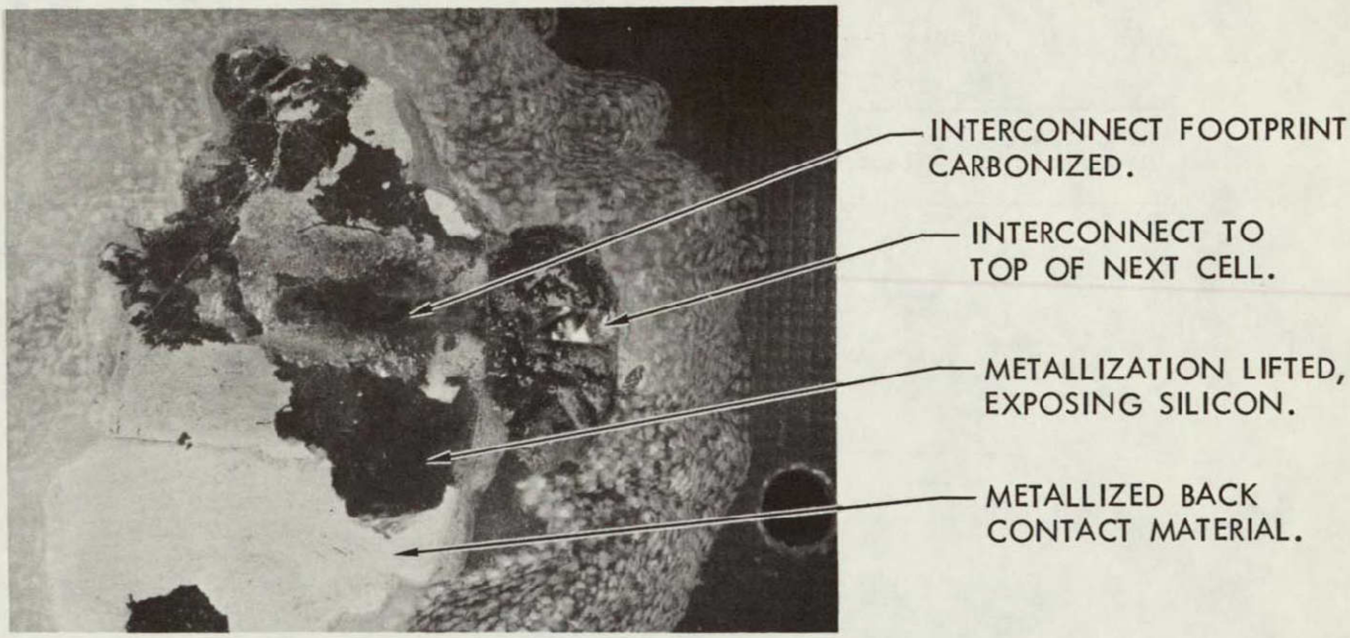

Figure 6-2. Separation of Metallization from Back of Cell

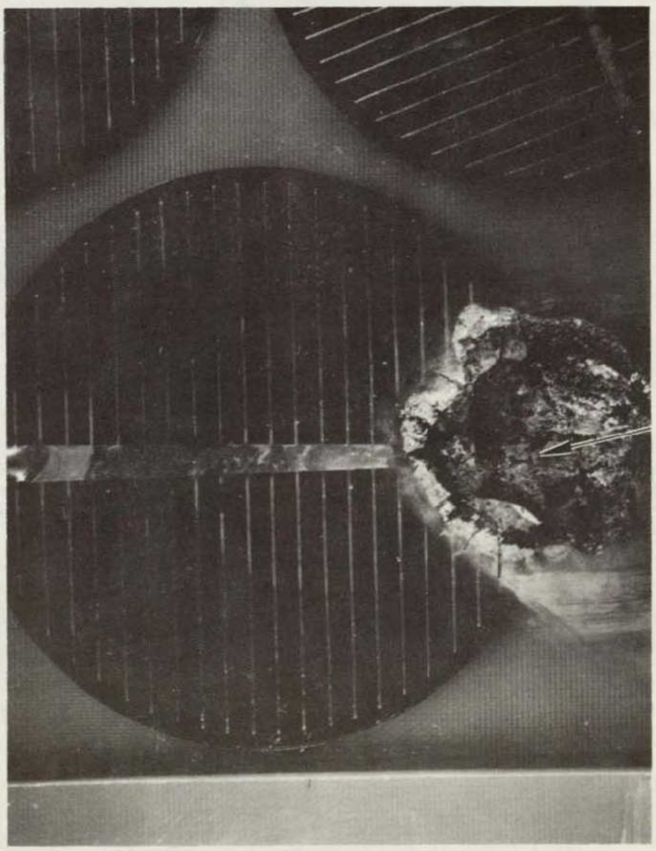

Figure 6-3. Carbonized Material Where the Interconnect
to the Bottom of the Cell Was Connected